Ver.2 with corrected slides #14-16

# Booster Collimation: 2-stage vs 1-stage

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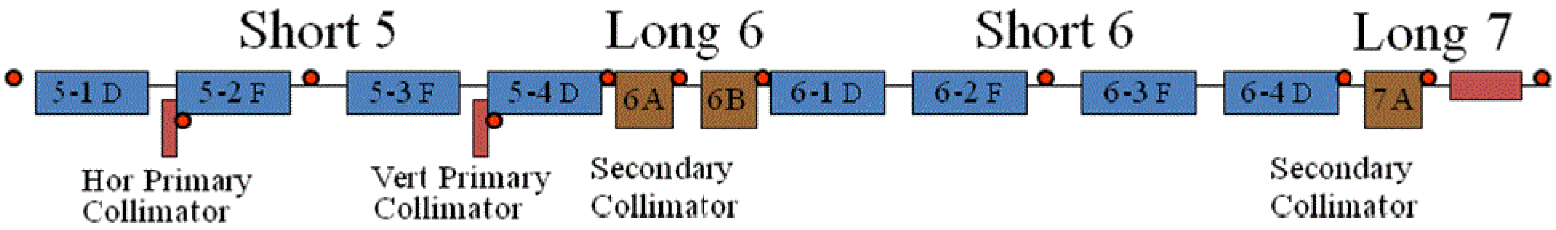
# Activities & acknowlegments to people involved

- 1) Booster Collimator Hardware & Control (motion tests) and Beam Studies:
  Charles Briegel, Salah Chaurize, Mike Coburn, Vladimir Sidorov, Matt Slabaugh, Todd Sullivan, Kent Triplett, Rick Tesarek
- 2) Support for Beam Dynamics Simulations:
  Valeri Lebedev, Nikolai Mokhov, Yuri Alexahin, Sergei Striganov, Igor Tropin
- 3) Support for task managments and planning:
  Bill Pellico and Cheng-Yang Tan

# Booster collimation activity and status




History

- 2-stage coll. system for booster designed & installed in 2004. Optimal primary foils at 400 MeV: 0.003mm W by "STRUCT+MARS" (or ~ 0.015mm Cu). *Instead 0.381 mm (thick!) Cu foil was installed*
- 2-stage collimation is not used in operations (due to variable beam size and positions < ~2014)

Programming & Simulations

- New MADX+MARS bundle for booster: proton interactions with PrCol & outscattering from Sec. Colls
- Calculated Coll. Efficiency < 60% (low & ~1-stage); Opt. foil ~50um for Cu. => 400um Al - installed
- Tools for post-processing of beam orbits (B38), BLMs (B136 & "a'la B88") have been developed

Beam study (in vertical plane)

- **Objective**: to understand if 2-stage coll. is better than existing 1-stage collimation
- Initial study of 2-st. collimation at low intensity: stable beam orbits (B38); BLMs are not timed relatively to one another (~300us), strange plots for some BLMs; Beam near detection thresholds for FastLMs;
- Analysis of BLM data: 2-stage vert. collimation works (fraction of p scattered by PrColl then lost on SecColL6A), but not optimized yet
- Second study: vertical collimation under full intensity (14-turns) done **on 29/Jun/2016. Presented here**.

Hardware repair & support

- Two broken BPM (upstream vert. in L06 & upstream hor. In L07) – were repaired before 2016 shutdown
- Sec. collimators motion: maintaining plan for summer shutdown (by Matt) - to sample the oil the from one of the collimator gearboxes & at least visually check the condition; to purchase a spare gearbox
- Some issues for BLMs data (B136) should be resolved (for future studies)

## **Objective**: to understand if 2-stage collimation is better than existing 1-stage collimation

### Why such task exists:

- There are **plans to increase Booster intensity**:
  PIP => 4.3E12 ppBc (15Hz) and further (~50%) to 6.5E12
- Present PIP efficiency: 92% (for 4.3E12) drops to 90% (for 5.3E12), and => <89% (for 6.5E12). **Losses are increased with intensity**!
- To remain at our present activation levels Booster needs to operate at around 95% efficiency (by **"beam physics" improvements**)
- **Improved collimation** potentially may help to **facilitate this task**
- Booster has installed a 2-stage collimation (2SC) consisting of 2 primary & 3 secondary colls. **Only 1-stage** (1SC) **is used now**.
- **Exp. capabilities of 1SC** are known (small improvements possible)
- Potentially well-designed **2SC can be better of 1SC**. However, it was **never demonstrated for booster**. (Due to non-optimal foils?)
- Our task to **compare 2SC and 1SC** and understand if 2SC can be useful for a booster intensity upgrade.

# Design principles for 2SC in synchrotrons: are they well established and proved ?

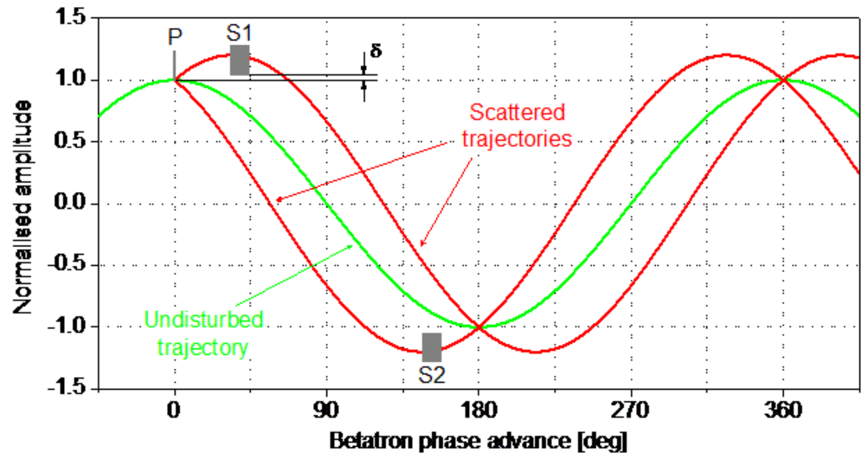
- Classical 2-stage collimation (2SC) designed in 2004 for **booster synchrotron** has been never applied for **synchrotrons** (var Energy & C.O.) by that time (SNS & JAERI were built later).
- **Design principles** have been **directly transferred** from Tevatron 2SC (collider with constant energy and stable beam orbits)
- Booster 2SC has been implemented into already **existing machine** installing collimators **in available spaces** between small-aperture magnets
- 2SC is effective within **narrow region of synchrotron circle** (e.g. injection)
- There is **no reliable & comprehensive simulations** comparing 2SC with single stage collimation (1SC) **for booster**. Automatically better ?
- 2SC systems at JAERI & SNS were designed for **new machines** (Disp=0)
- JAERI (RCS) **in similar way** with STRUCT (later re-simulated with ORBIT). Used in operations; but no comprehensive data published (why?). Later additional collimators were installed at H-minus injection area.
- SNS **does not use installed 2SC** (not needed due to large apertures). published beam study results did not show positive effects from 2SC
- RAL uses set of many thin and thick collimators (**not a classical 2SC**)
- SNS,RCS,RAL use thicker prim-colls (tanks to larger apertures) => larger rms scattering angles => larger impact params. => smaller out-scattering

# 2SC as an improvement of 1SC

Usual “1-stage” collimation produces **uncontrolled out-scattered protons**
=> “2-stage” scheme (icreasing impact parameter on sec.colls)

From Ivan Strasik (GSI) 2014 talks

- Primary collimator (thin foil) – scattering of the halo particles
- Secondary collimators (bulky blocks) – absorption of the scattered particles




- Particles have small impact parameter on the primary collimator
- The impact parameter on the secondary collimator is enlarged due to scattering

Very robust concept and well established in many accelerators.

*[Ref] M. Seidel, DESY Report, 94-103, (1994)*
*[Ref] T. Trenkler and J.B. Jeanneret, Particle Accelerators 50, 287 (1995)*
*[Ref] J.B. Jeanneret, Phys. Rev. ST Accel. Beams 1, 081001 (1998)*

# 1SC efficiency depends on several params.

1SC depends on impact parameter & angular alignment of jaw

M. Seidel example: Out-scattering reduces to 0.4 within [+-0.05mrad]

M. Seidel The Proton Collimation System of HERA DESY 94-103 June 1994 Dissertation

**2. 3. 3 Simulation Results**

In this chapter we present simulations made with a single collimator jaw. Tracking simulations of the complete system are presented in chapter 3. The most obvious result is the strong dependence of the absorption efficiency (and also the rms-deflection angle) on the angular alignment of the jaw (see also [SEI92]). If the jaw is misaligned as depicted in Fig. 2.15 the effective collimator length is reduced.

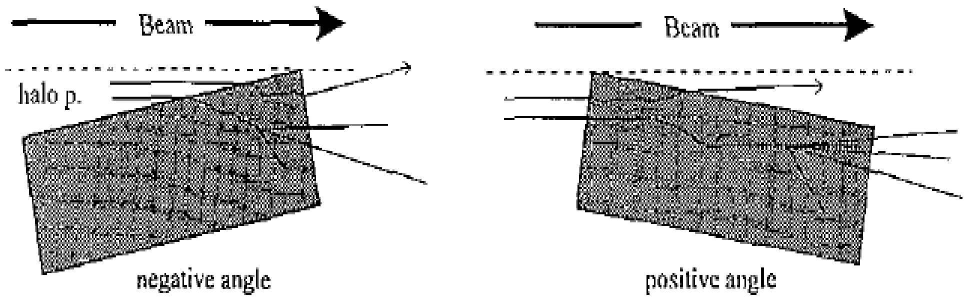
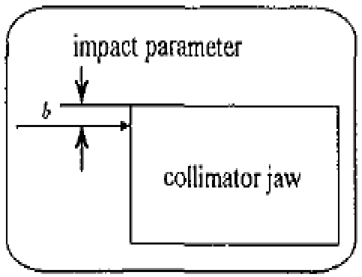



Fig. 2.15: Reduction of the effective jaw length due to angular misalignment.



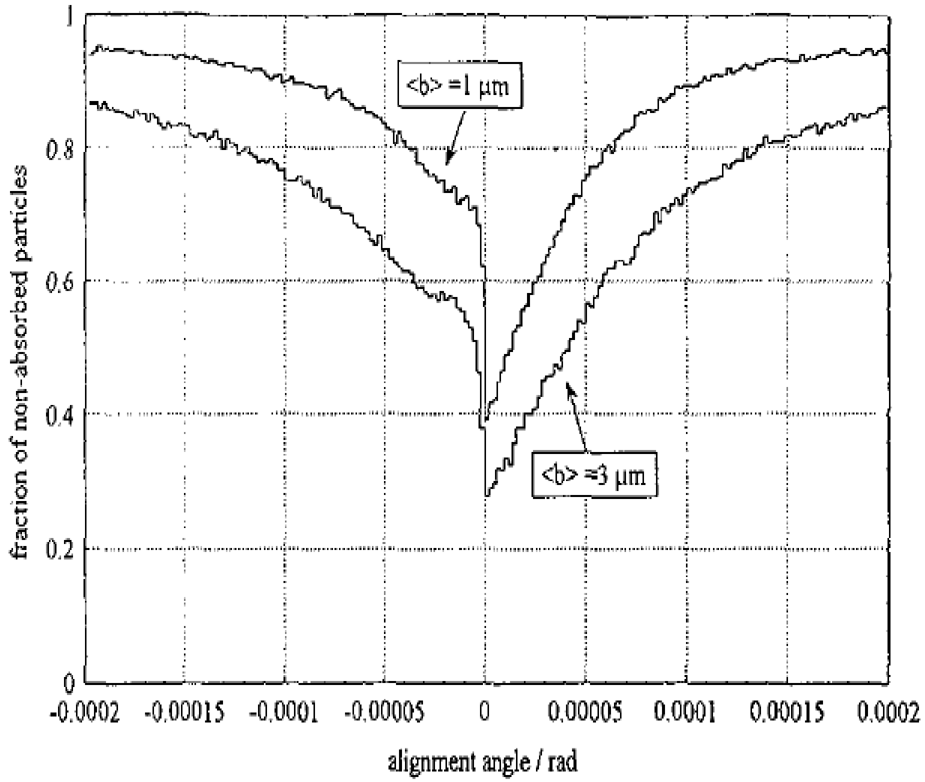



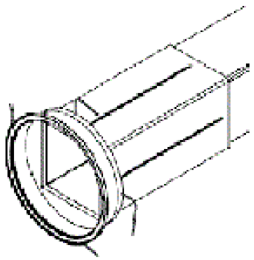

Fig. 2.16: The out-scattering probability as a function of alignment angle for two different exponential impact parameter distributions.

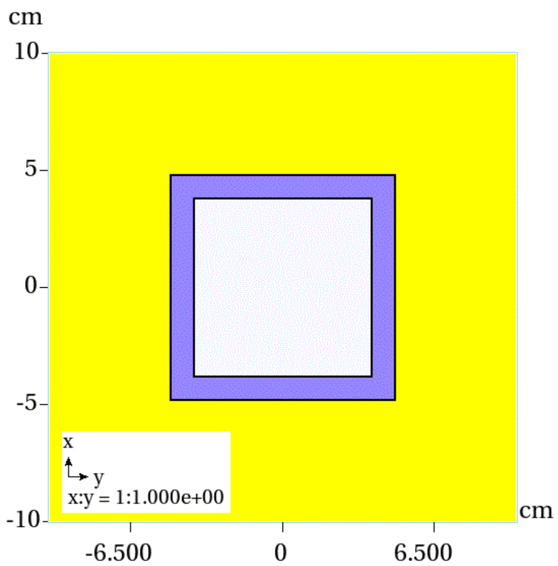
Collimation efficiency may also depend on particular features of **jaw configuration** of secondary. collimators

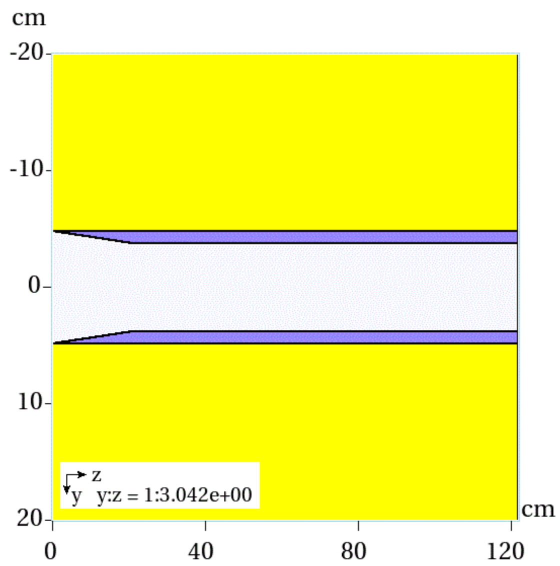
# Simulations with MARS model for secondary collimators

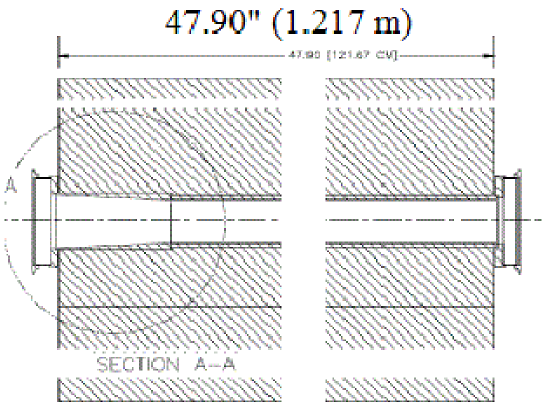
Model created and supported by I. Tropin & N.Mokhov; Interface with “STRUCT” coordinate system (x,x’,y,y’,p); Model is centered on ref. orbit.

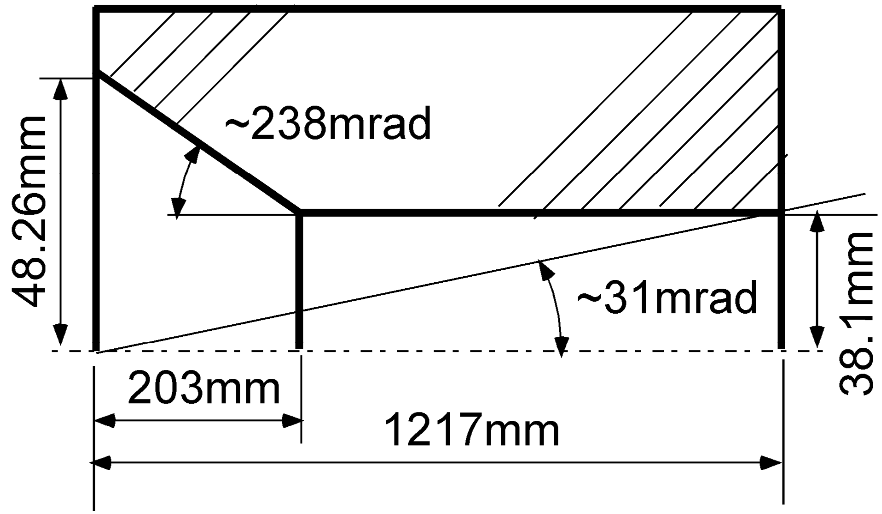
Original drawings;
MARS visualization;
**relevant sizes & angles**





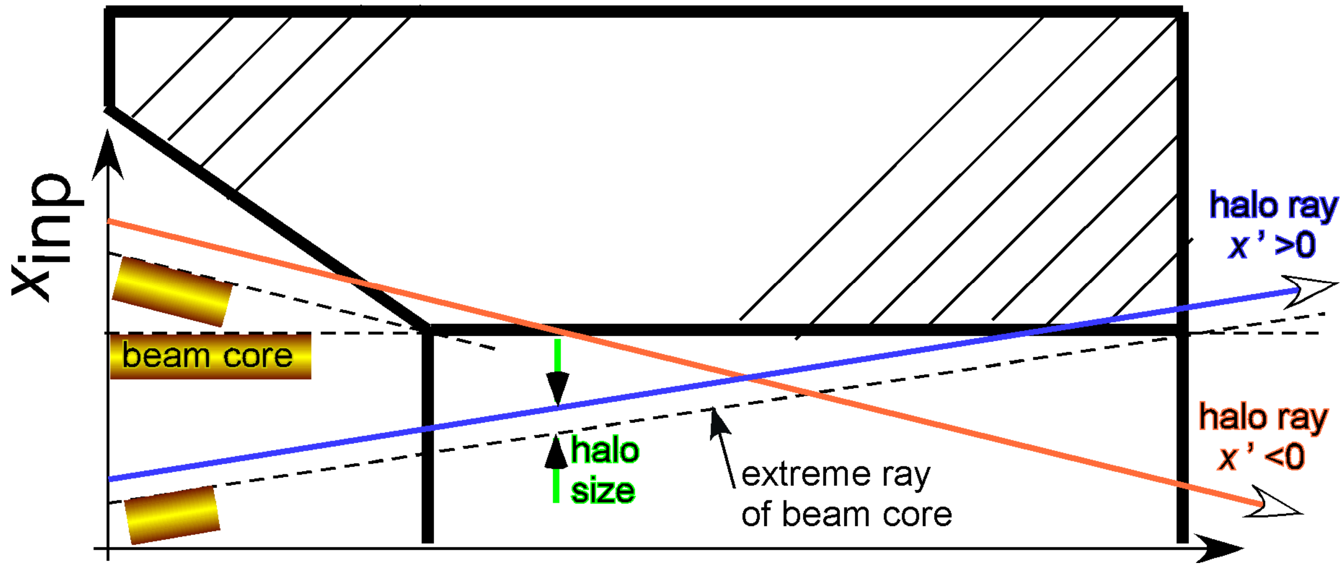



# 1SC: simulation scheme

halo ray (10^4 protons with identical coords); dependence on slope x'=dx/dz [mrad] at given halo sizes

*Note: modern (>2005) collimators have similar "tapers" at both front & back jaws*





For **x'>0** beam hits **back** jaw

For **x'<0** beam hits **front** jaw

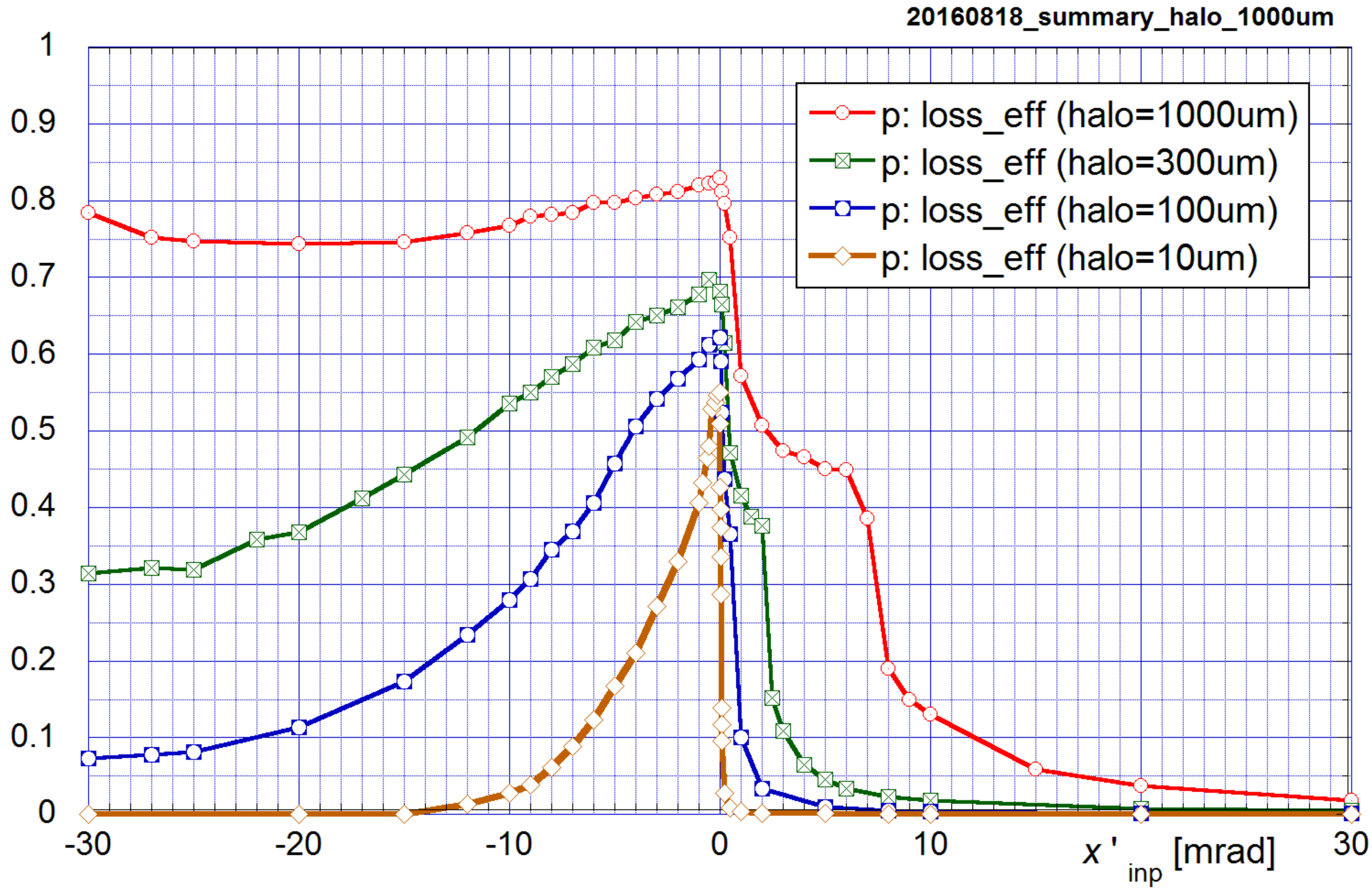
Condition:

beam core touches jaw w/o losses

Left: Relation between input x' & x for a given halo size (here 1mm)

# 1SC simulation: eff. vs x' at diff. impact parameters

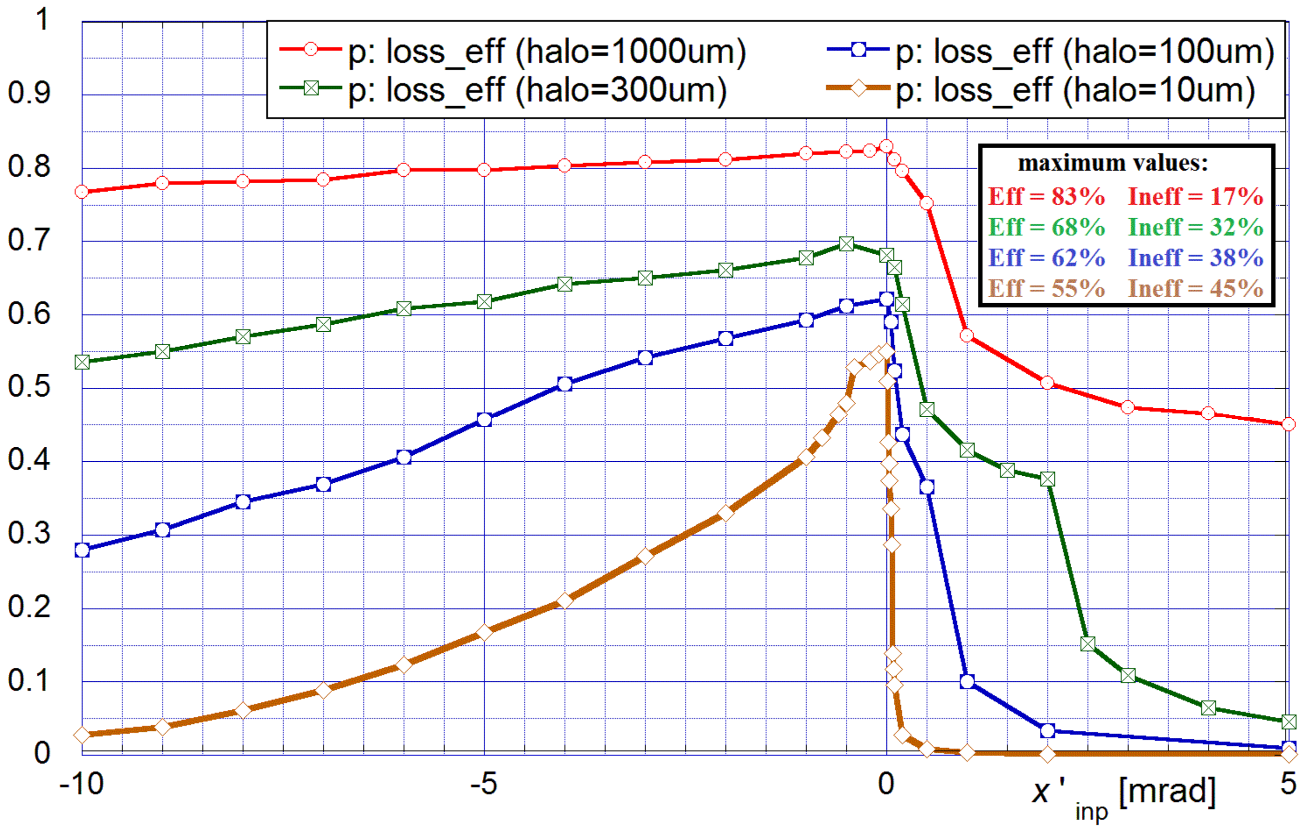
"1SC Eff."=(N protons lost in collimator)/(N=10^4 parts in incident beam)



# Imaginary goal-values for 2SC

Assuming that 2SC can reduce (collimator related) losses of 1SC by **50 %:**

| Halo [um] | 1SC Ineff | 2SC Ineff | 2SC Eff |
|---|---|---|---|
| 10 | 45 % | 45*0.5 ~23 % | (1-0.22)=77 % |
| 100 | 38 % | 38*0.5 =19 % | (1-0.19)=81 % |
| 300 | 32 % | 32*0.5 =16 % | (1-0.16)=84 % |
| 1000 | 17 % | 17*0.5 ~ 9 % | (1-0.09)=91 % |




Need to evaluate "Halo per turn"= Impact param.

Collimator related losses ~ Inefficency:

Let's define "1SC Inefficiency" = (1- Eff.)~ (N_outscat/N incident)

# Ways for “halo” evaluations

**1) Numerical simulations** (e.g. Synergya code) can help to evaluate minimum values of beam halo. It is more adequte for rings with constant parameters.

(A. Macridin & V. Lebedev did some evaluations. Details are not published)

***Actual “Halo-growth rates”*** in synchrotrons (with var. params) should be **higher** due to many real effects (variations of orbit, energy, misalighnments, mismatching etc.)

**2) Indirect experimental evaluations (feasible ?)** using the dependence Eff=(x’)
It suggests Efficiency drop (say 20 %) within: a) 1.5mrad, if halo ~10um;
b) 4mrad, if halo ~100um; c) 10mrad, if halo ~300um; d) none, if halo > 1mm

**Aperture Restrictions, e.g. Long 6 collimators:**

Distance between COL1 front and COL2 back L=4m

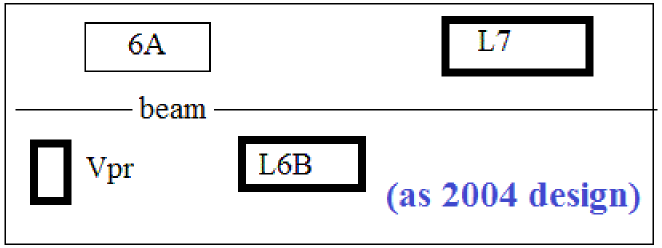
Max beam core sizes (~5sigma) = 19mm/32mm (H/V); Collimator a=38mm

Max angle x’=2*(38-19)/4 < 9 mrad; y’=2*(38-32)/4<3mrad;

*May be possible to evaluate for hor. plane x’, if the halo rate within or > 100um ?*

*Todd: regular change of x’ with dX(BPM)=+-2mm =>4mm/5m <1mrad*

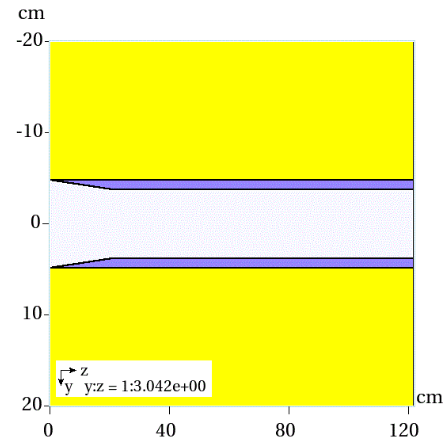
# Simulation of 2SC in vert. plane




My conventions for Boo **2SC setup** (1.*=hor; 2.*=ver)

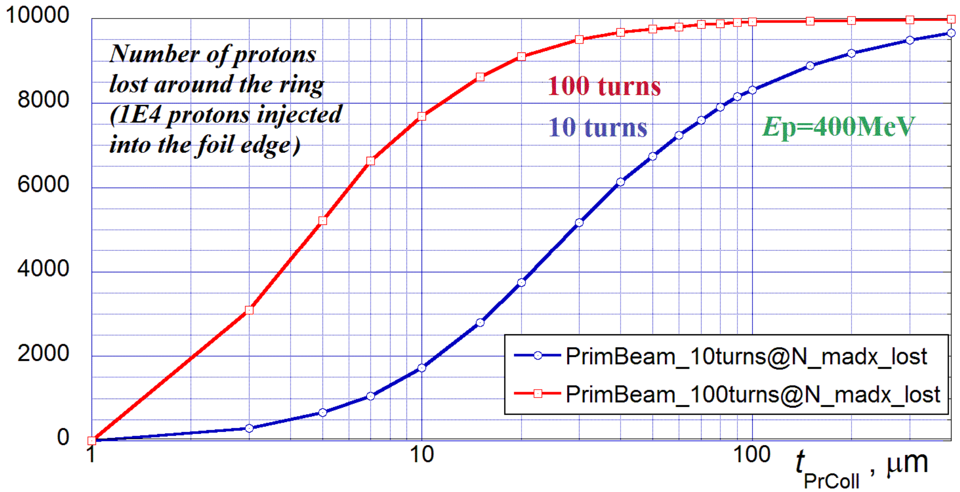
- Mode 2.1) **"2004-design"** COL {Vp,1,2,3}={-;"0";-;+}, where "+/-"=top/bottom, 0 - garage
  if **V-prim** on **bottom** beam edge (mode2.1), then:
  a) only **COL3(L7)** has mu>90deg, it must come from opposite (**top**) edge;
  b) both COL1&COL2 can be used for mu<90deg, but larger mu-preferable (large delta-gap) and free COL1 for Mode=1.*. Then, **COL2** should be set on the side of V-prim (**bottom**)
  1c) if "b"=OK, then **COL1** should be in garage (or at least not on the bottom). It may be set at **top** with a large gap from beam edge to avoid direct beam interception (as for 1-stage scheme)

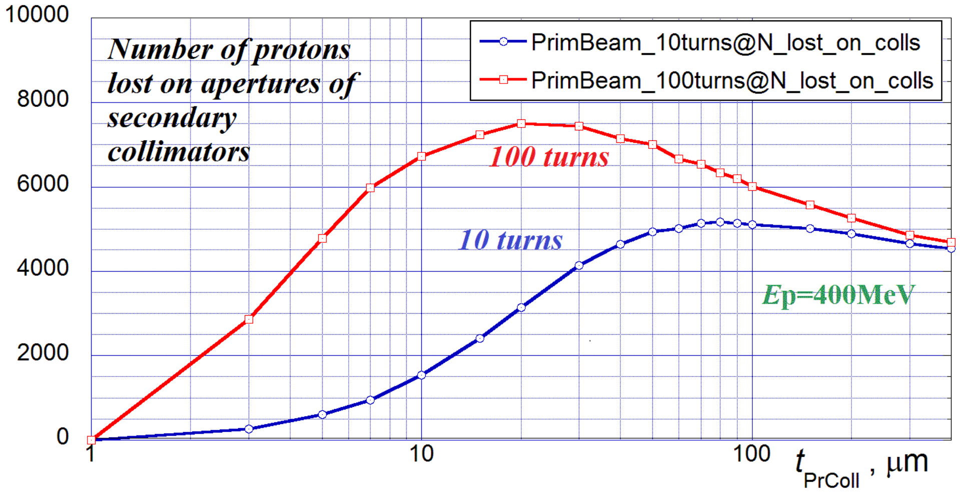
*One MARS model for 3 identical sec-colls.*
*Model is centered on ref. orbit.*
*Transverse shifts simulated via shift of input and output particle coordinates*




*Steps:*
*a) MADX multi-turn tracking with usual losses on apertures ;*
*b) protons lost on collimators collected at collimator fronts;*
*c) that protons are re-tracked throughout sec-colls with MARS;*
*d) Out-scattered protons are collected at sec-coll ends are tracked again by MADX*

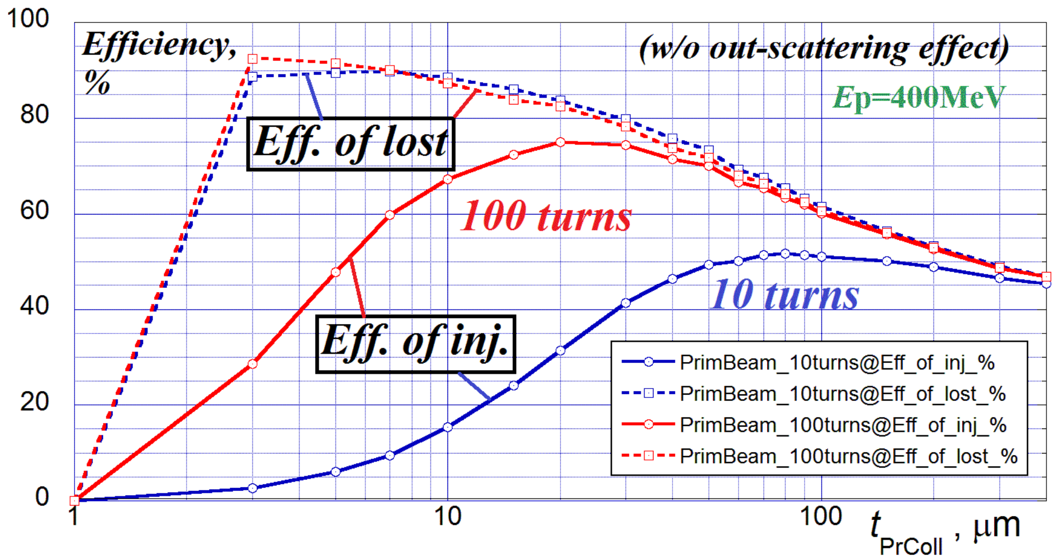
# a) MADX tracking (losses on apertures) vs t-foil (Cu)




**Efficiency definitions:** a) "Eff. of lost" = (N lost on colls) / (N total lost on the ring);

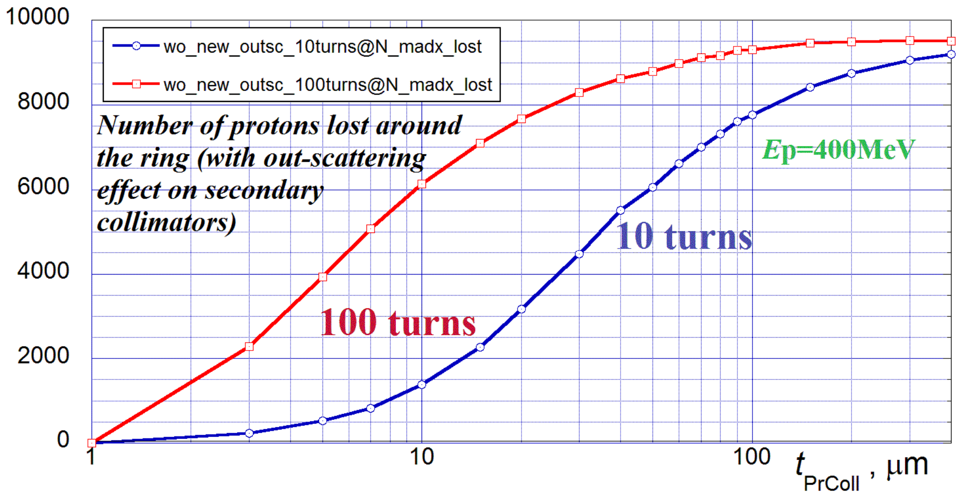
b) "Eff. of inj" = (N lost on colls) / (N injected on foil = 1E4)

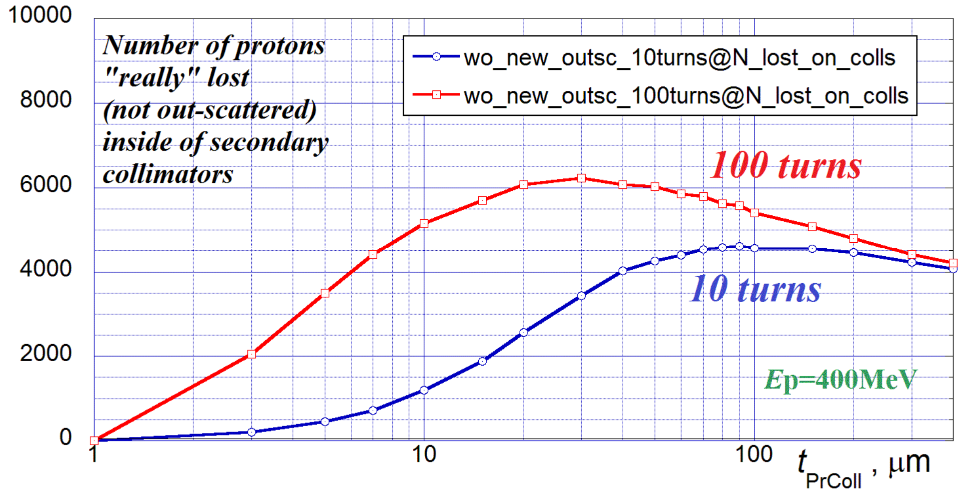



*Def. a): "no worry" about particles which were not lost in simulations. In reality they will spread & lost around ring due to their worsen 6D-coordinates after interaction with the primary foil*

Idea of 2SC is to insert prim. foil and catch most of scattered protons (say >90%) by sec. collimators => Use def. b) "Eff. of injected" !!!

# c) MARS re-track “lost” p in Sec.colls (out-scattering!)

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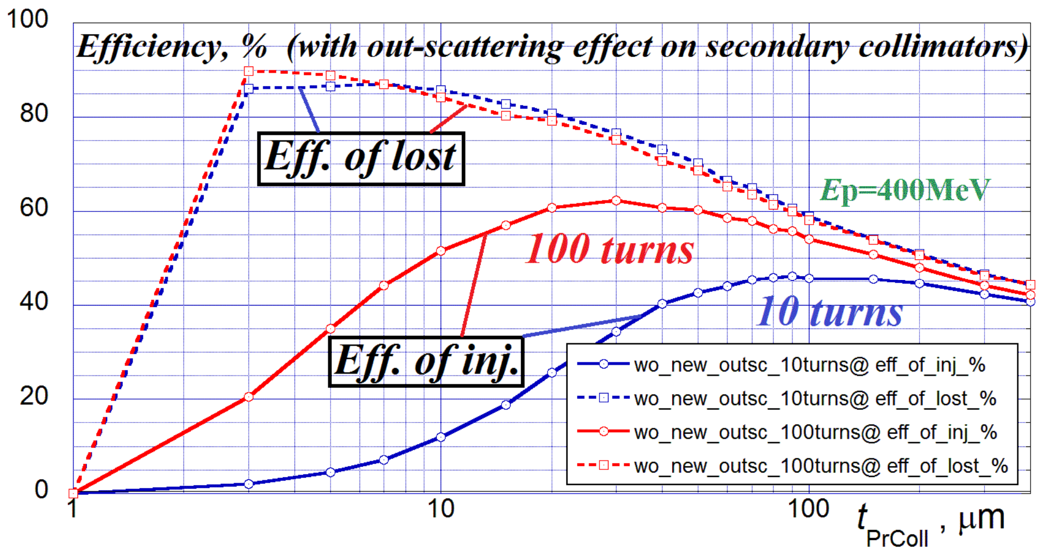



*Def. a): very optimistic efficiency for ultra-thin; what about the fortune of not-lost (& out-of-control) >4000 particles with worsen 6D-coordinates by foil ?*

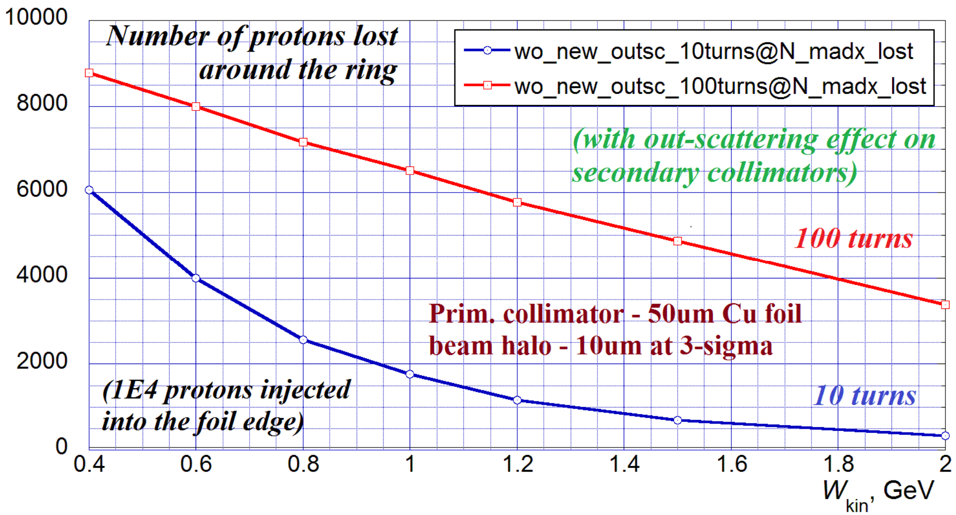
b): “Eff. of injected”

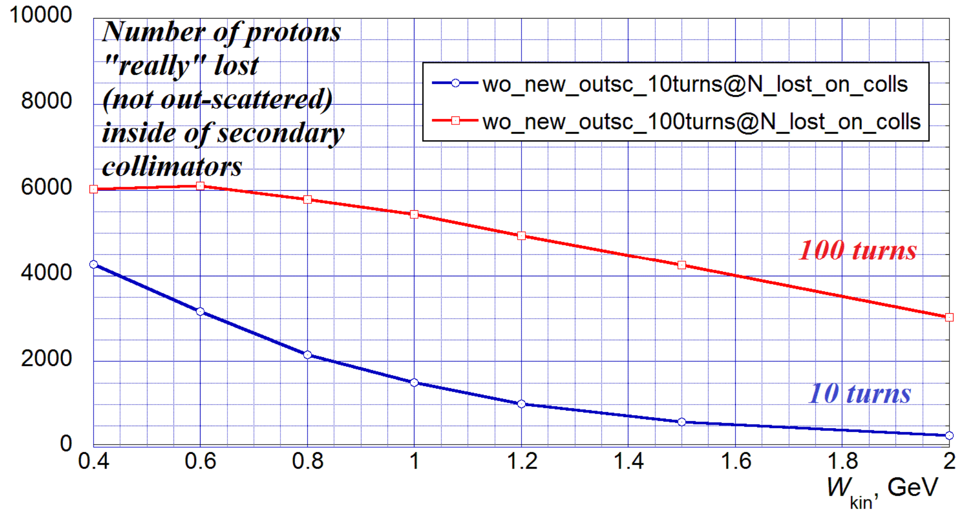
- max 46%(10turns) & 62%(100turns)
- for new installed 380um Al foil (~50um Cu) – 42% (10) & 60%(100)

=>

close to maximum efficiency

# Eff. vs Energy for new 380um Al (~50um Cu)

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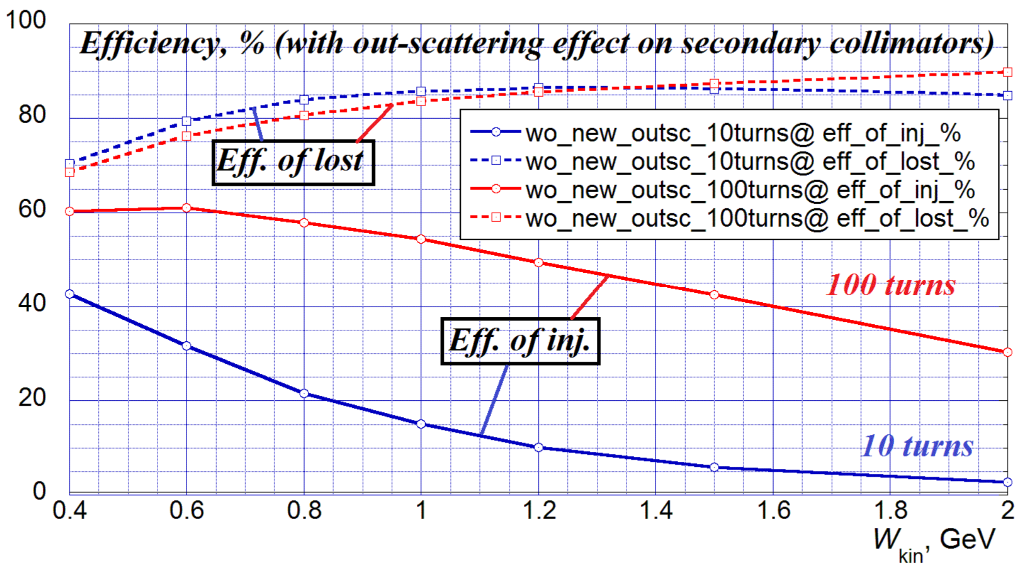


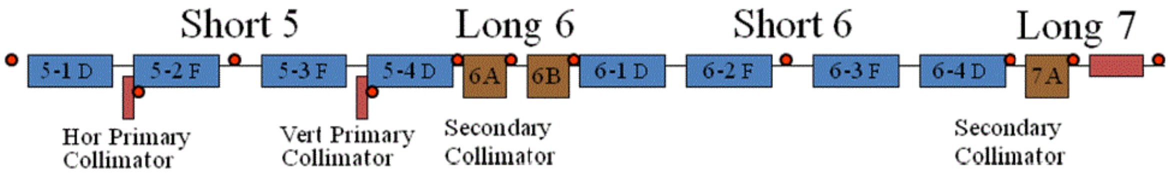

*Def. a): eff. slightly increased with Wkin*

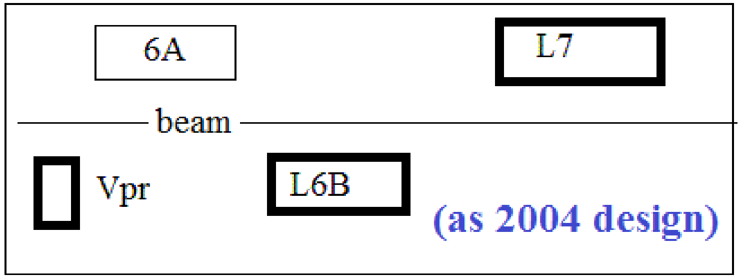
*b): "Eff. of injected"*

- *10 turns: max eff. 43% at 0.4GeV*
- *100 turns max ~61% near injection (0.4÷0.6GeV)*
- *Eff. drops with increase of Wkin*

*Even max eff. of ~60% (100turns) is near the same as 55% for 1SC (at halo ~10um) !!!*

# 29-Jun-2016 Beam study: Vert 2SC

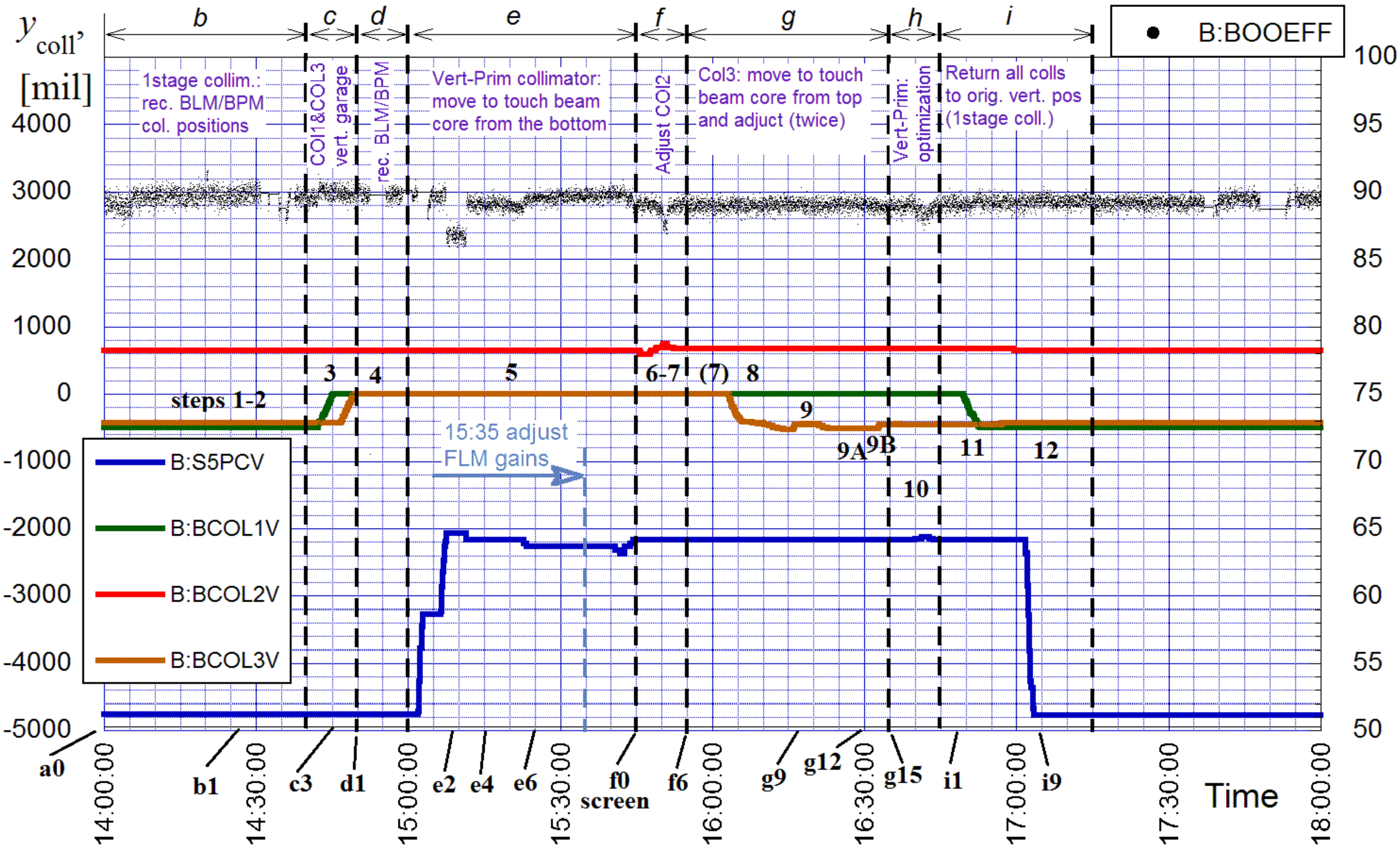



Actual Study Steps & time intervals

| | | | | | |
|---|---|---|---|---|---|
| 1-2 | *b* | *Record BLMs, BPMs Coll-pos* | 8 | *g* | Move Col3-L7 toward to beam (DN) to touch beam core |
| 3a | *c* | Move Col1-L6A vert. garage | 9 | *g* | Adjust Col3-L7 to beam core & move away (UP) ~2mm |
| 3b | *c* | Move Col3-L7 vert. garage | 9A | *g* | Adjust Col3-L7 again |
| 4 | *d* | *Record BLMs & BPMs* | 9A | *g* | *Record BLMs & BPMs* |
| 5 | *e* | Move Vprim to touch beam core from bottom | 9B | *g* | Move Col3-L7 (UP) from beam core ~2mm |
| 6 | *f* | Move Col2-L6B away from beam (DN) | 10 | *h* | Play with Vprim position |
| 7 | *f* | Adjust Col2-L6B to beam core & move away (DN) ~2mm | 11 | *l* | Return all Colls to 1SC: Col1-L6A; Col3-L7; Col2-L6B; Vprim |
| (7) | *g* | *Record BLMs & BPMs* | 12 | *i* | *Record BLMs & BPMs* |

# Time intervals & (corrected) plan steps

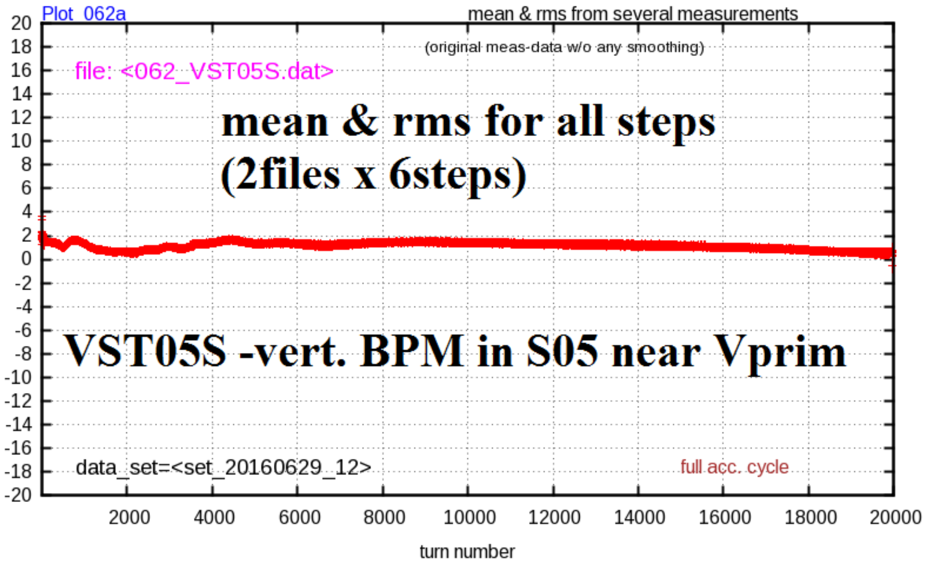


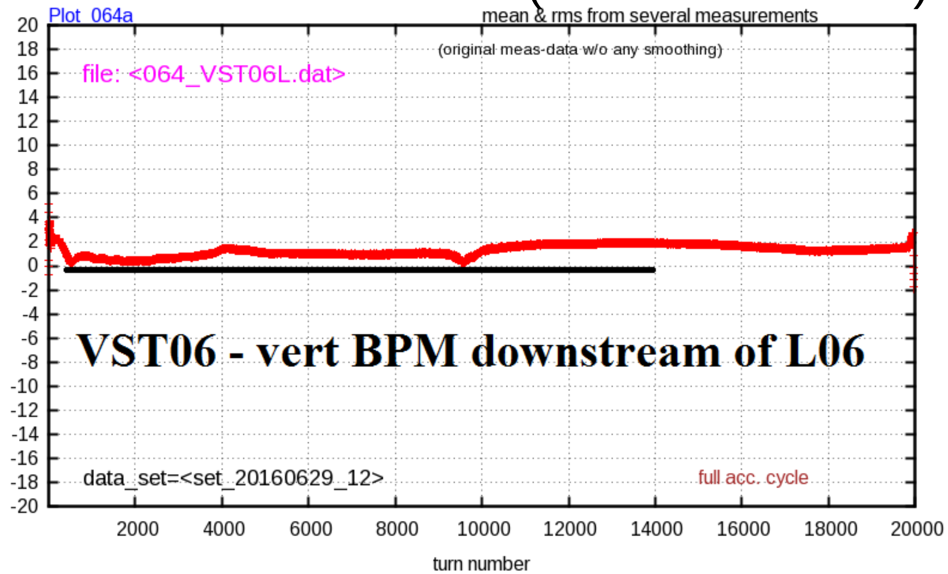
# ACNET applications used & post-proc .code

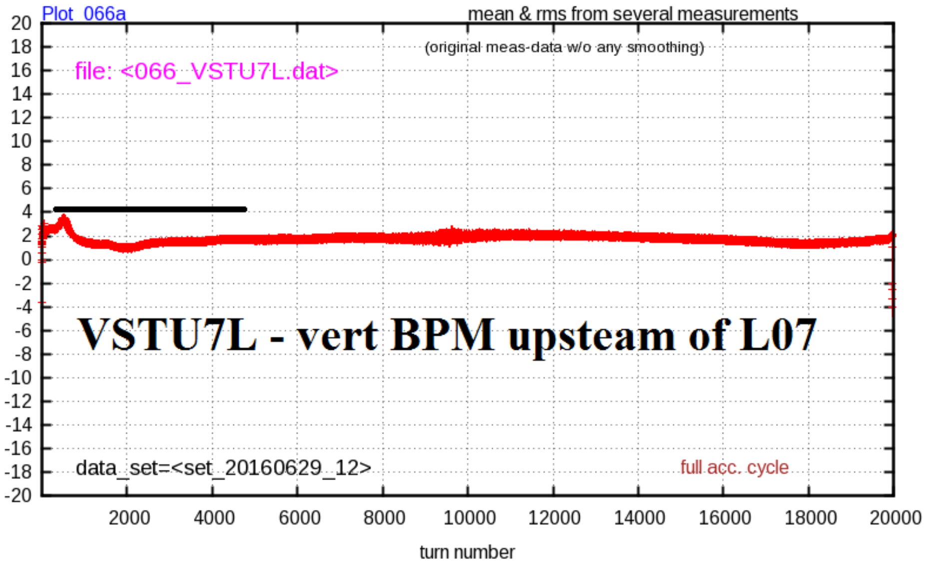
| | |
|---|---|
| B:BEFF17 | Beam transmission efficiency control |
| B38 Beam orbits | save data => postproc. code: x & x’ at collimators |
| D43 save-list | BLM data recorder for off-line usage via D44 |
| FLM signals | on-line for Collimator tuning; off-line via D44 |
| B88 “frac.trip point” | Data export does not work => only “PrintScreen” |
| A’la “B88” | Exe for reading BLM data to reproduce B88 plots |
| B136 BLMs signal within Boo-cycle | Save data => postproc. Code: check bad signals; averaging over cycle => compare with B88-plots |
| D44 | Off-line plotting of recorded parameters |

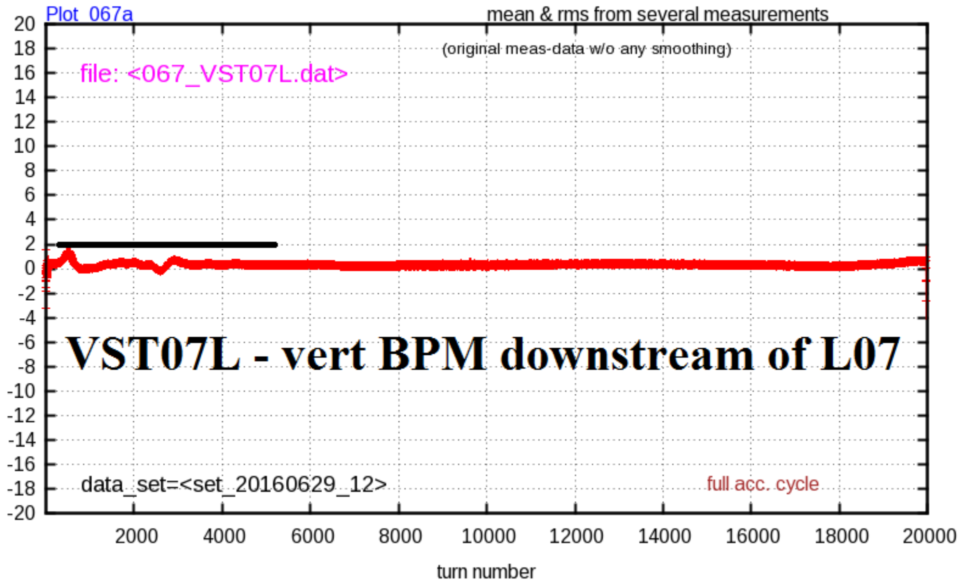
# B38 post-processing: Vert-BPM in S05; L06; L07

Measurements! (VSTU6L - broken)



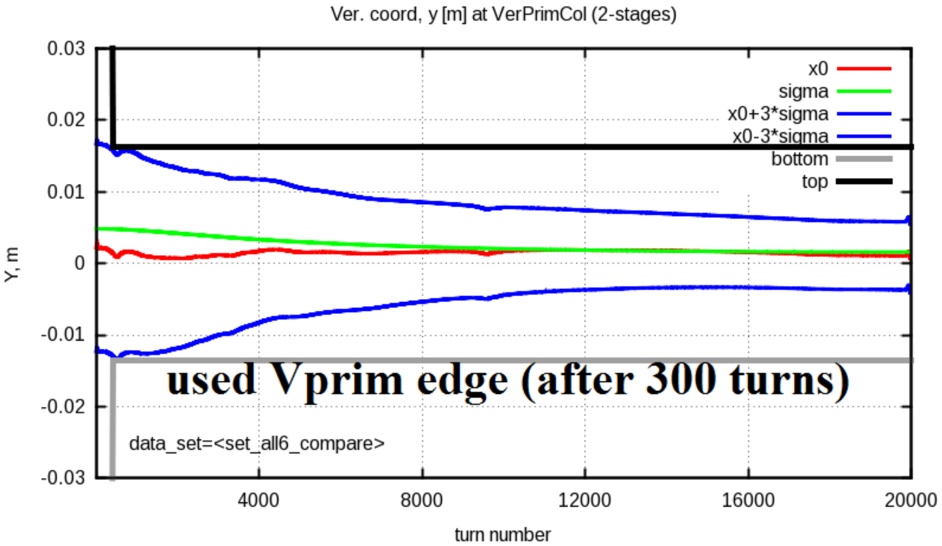



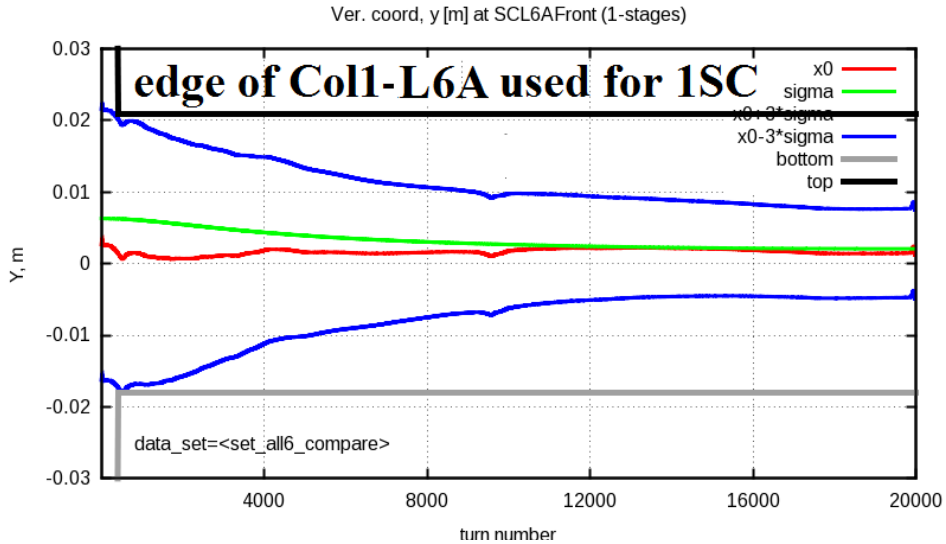



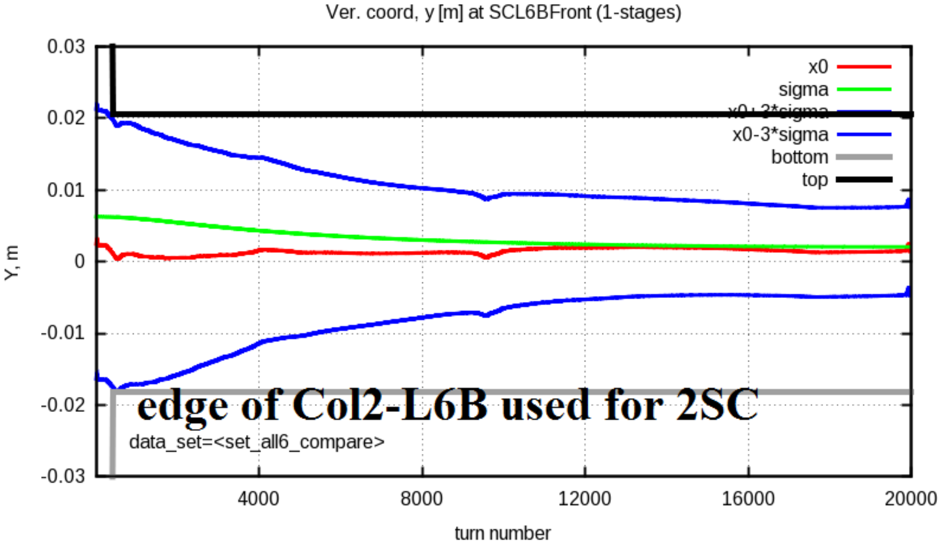



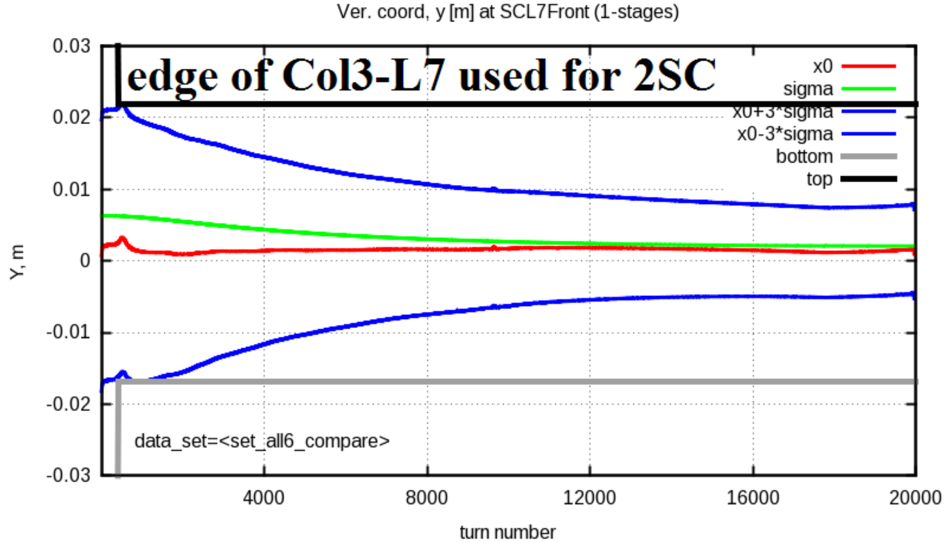

Beam orbit are stable during all steps of study !

# B38 post-processing: orbits at Vert-collimators



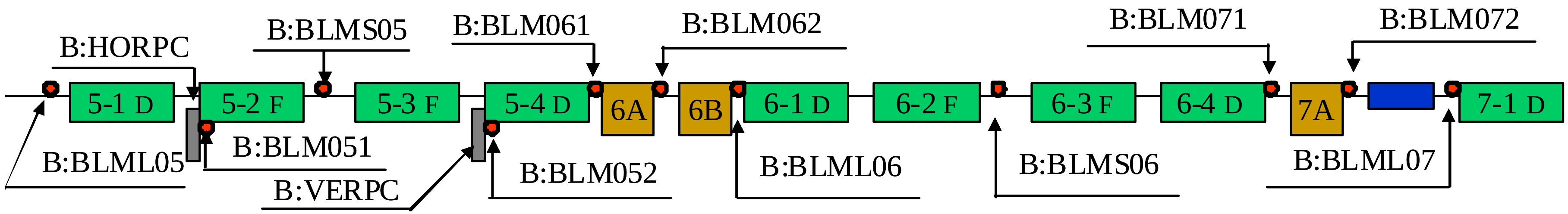



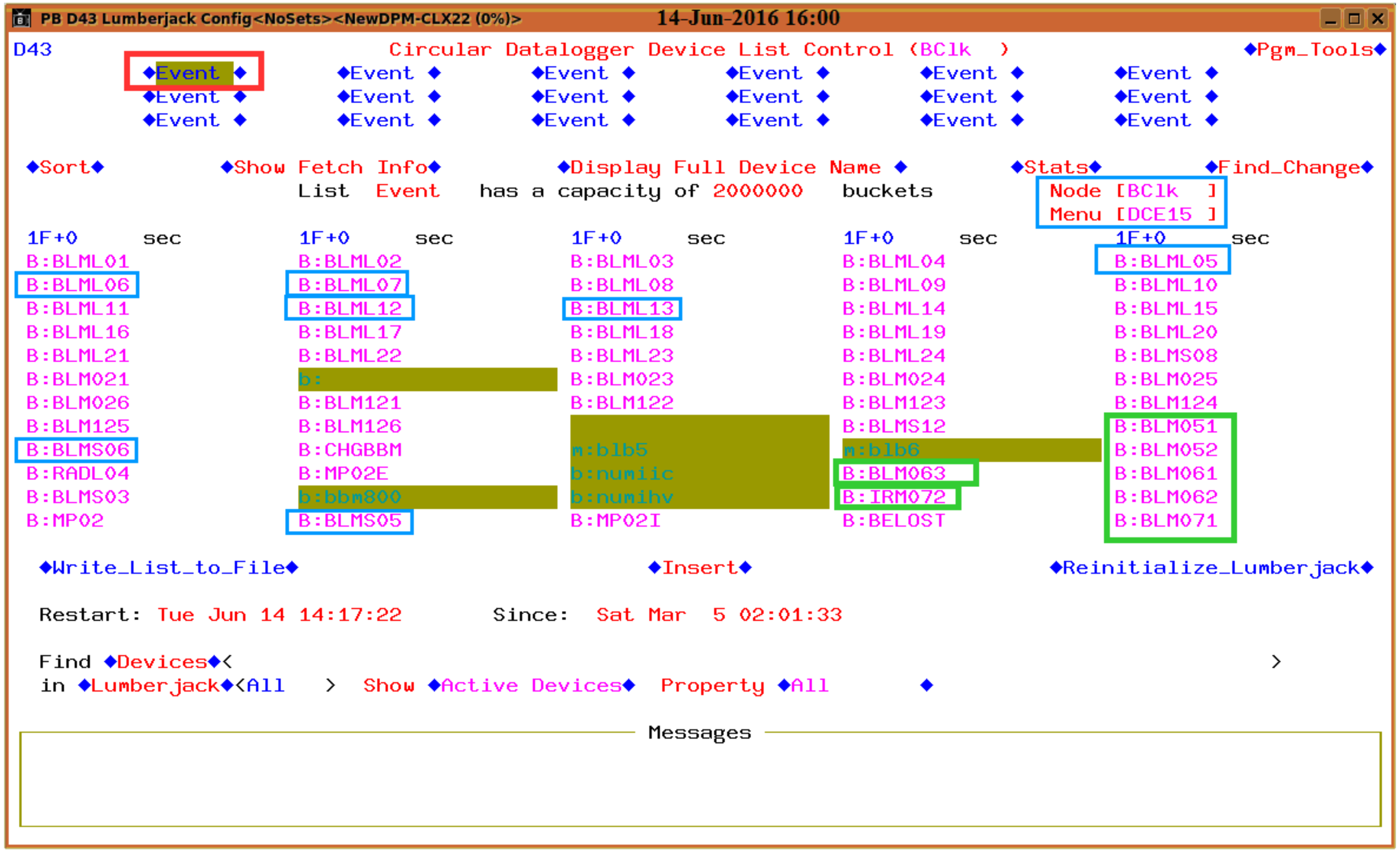




*Specially arranged bumps of 3-sigma envelops (by Todd)*

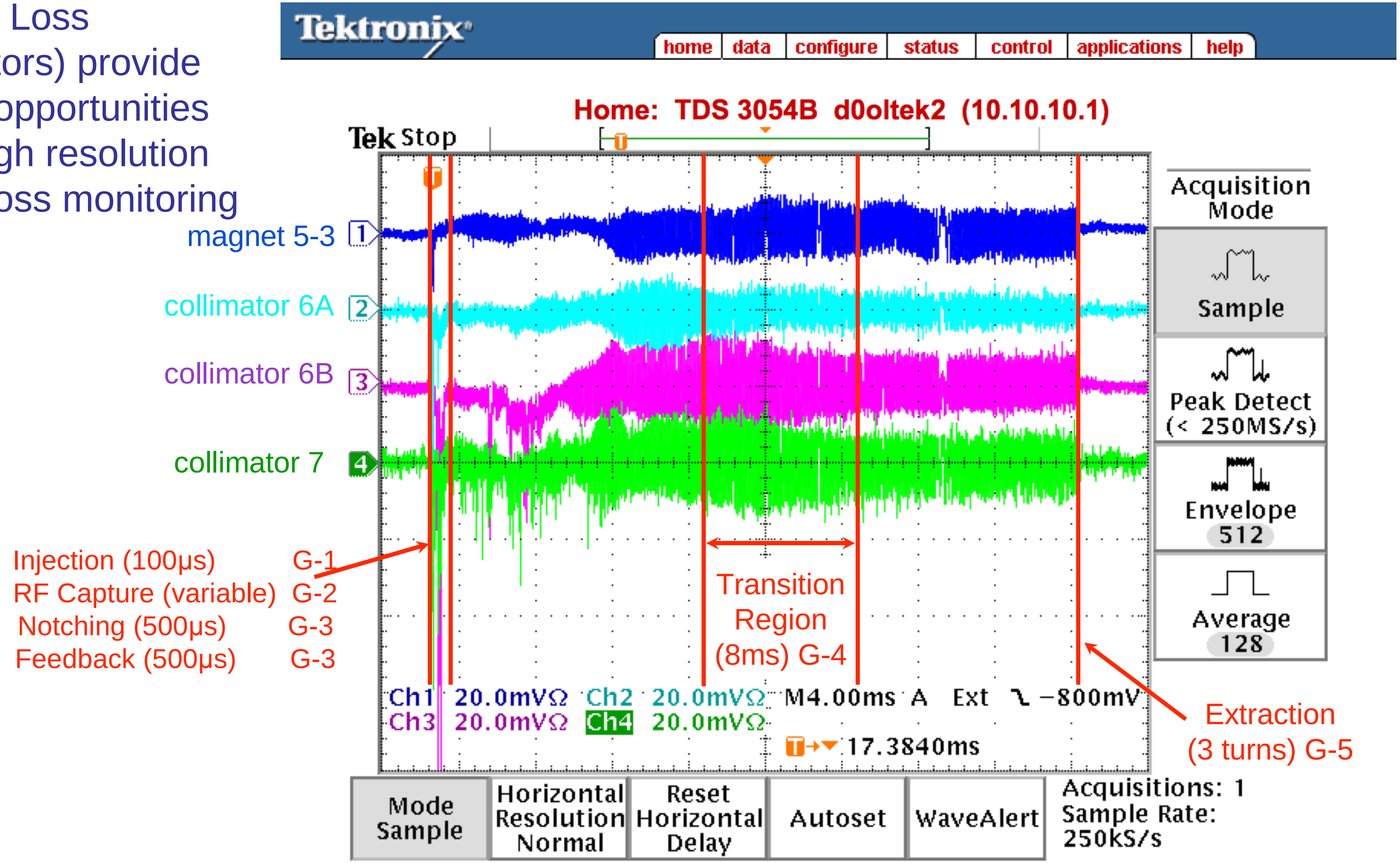
# D43 save-list: BLM data recorded



# Booster losses: FLM for full booster cycle

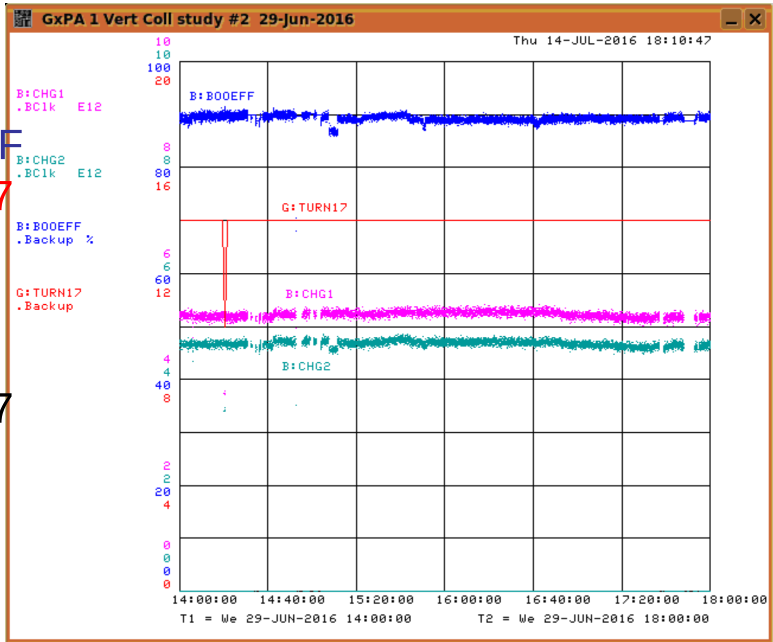
Rick's FLMs (**Fast** Loss Monitors) provide ***new*** opportunities for high resolution (ns) loss monitoring

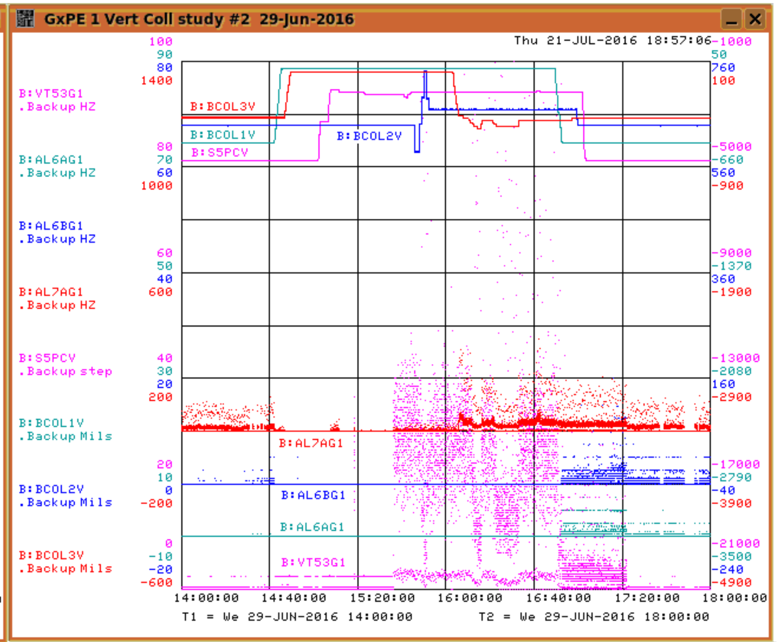


# Typical screens for tunings with FLMs (2-6pm)

D44:
BOOEFF
TURN17
CHG1
CHG2

TURN17
=14

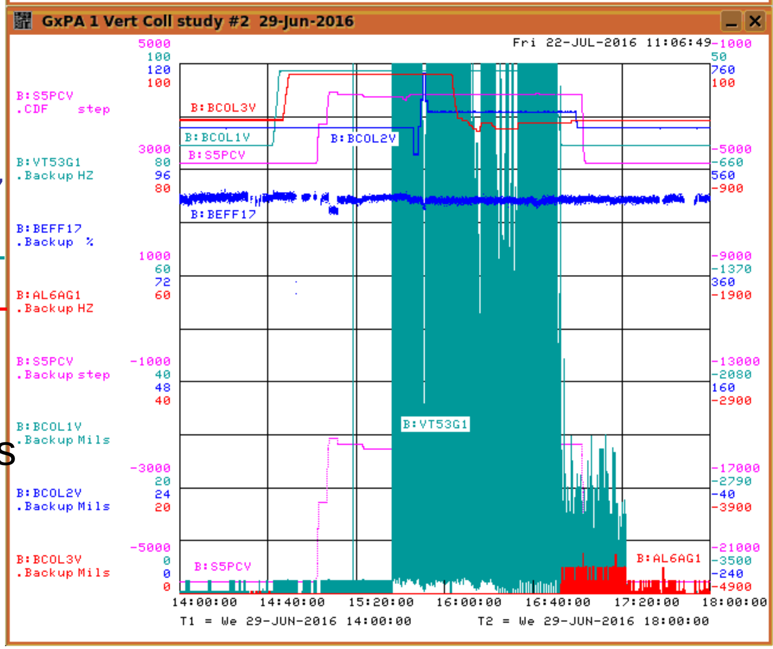


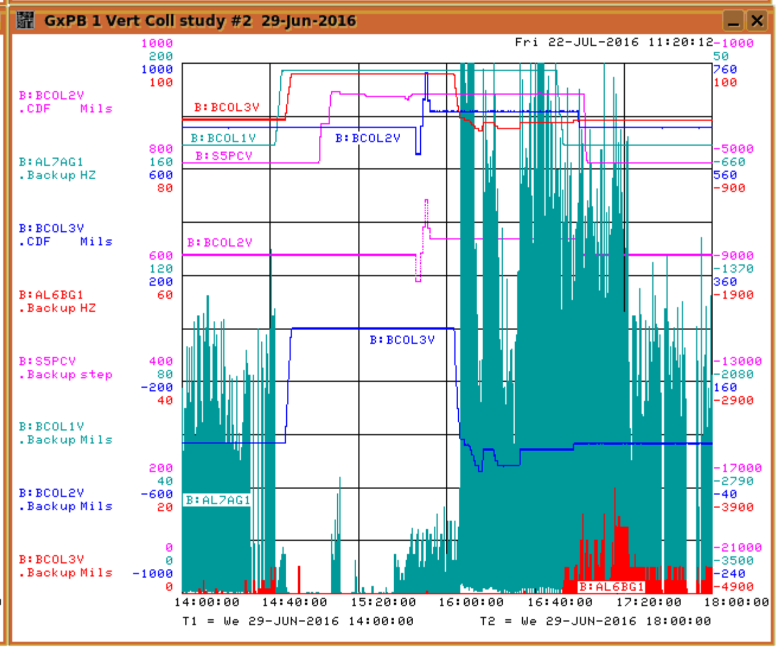




D44:
VT53G1
AL6AG1
AL6BG1
AL7AG1
&
Coll.
positions

D44:

BEFF17
VT53G1
AL6AG1
&
Coll.
positions




D44:

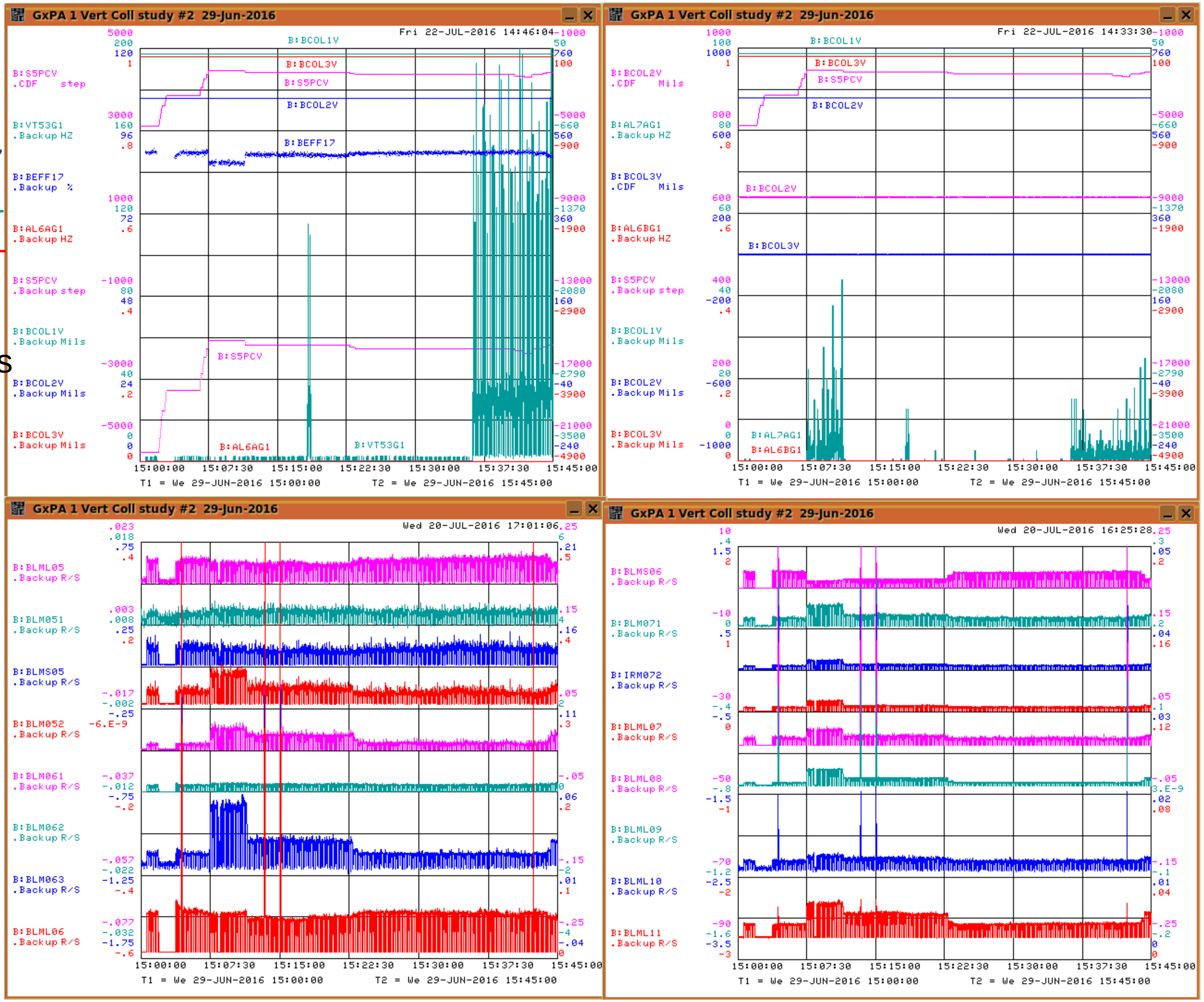
AL7AG1
AL6BG1

&
Coll.
positions

# Tuning Vprim: “e”-interval (15:00-15:45)

D44:

BEFF17
VT53G1
AL6AG1
&
Coll.
positions




D44:

AL7AG1
AL6BG1

&
Coll.
positions

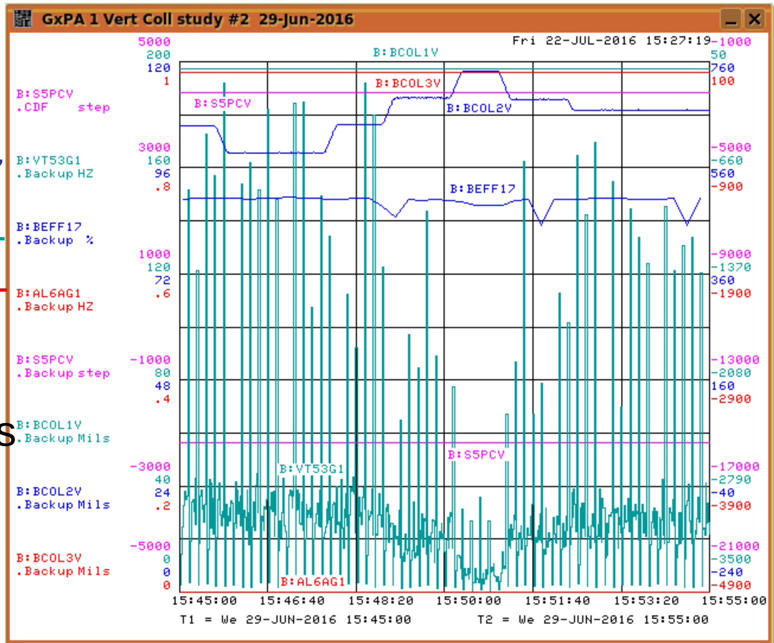
BLMs
In D43
list:
L05,
051,
S05
052,
061
062
063
L06

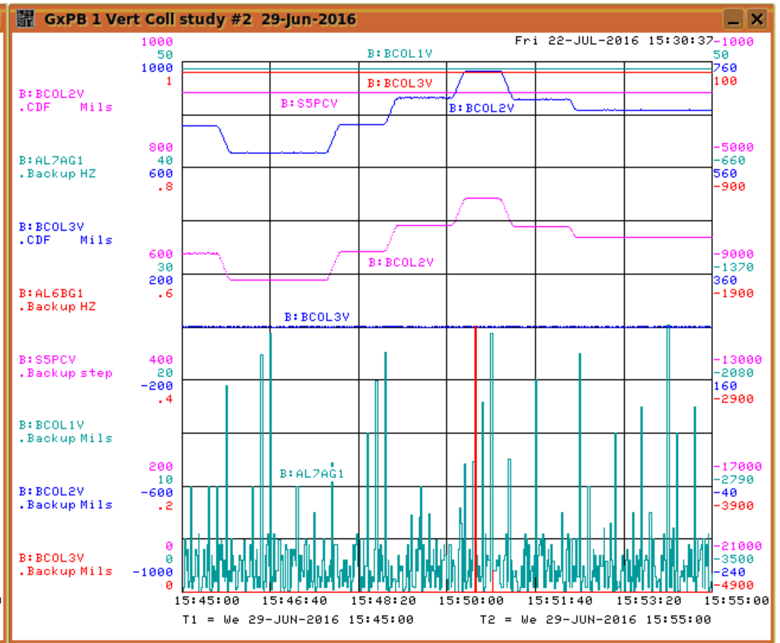
BLMs
In D43
list:
S06,
071,
072,
L07
L08
L09
L10
L11

# Tuning Col2-L6B: “f”-interval (15:45-15:55)

D44:

BEFF17
VT53G1
AL6AG1
&
Coll.
positions



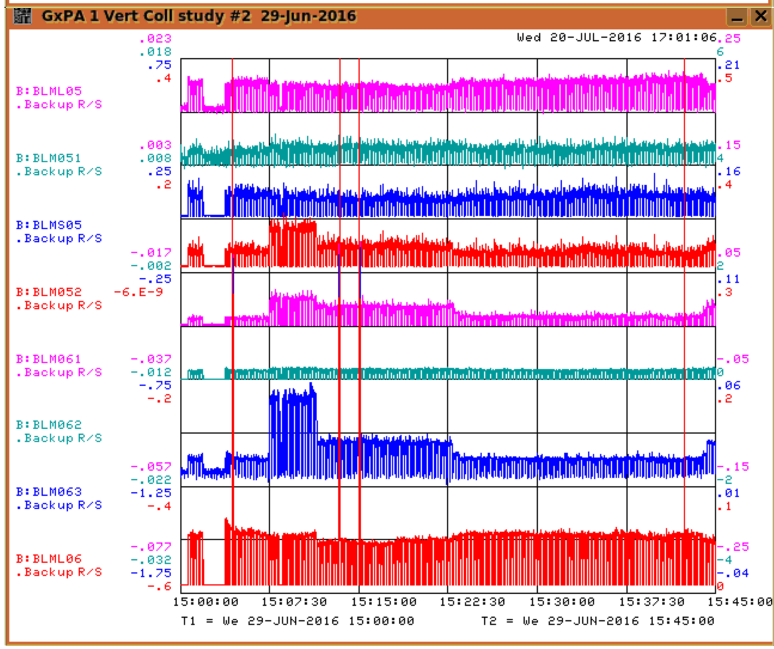



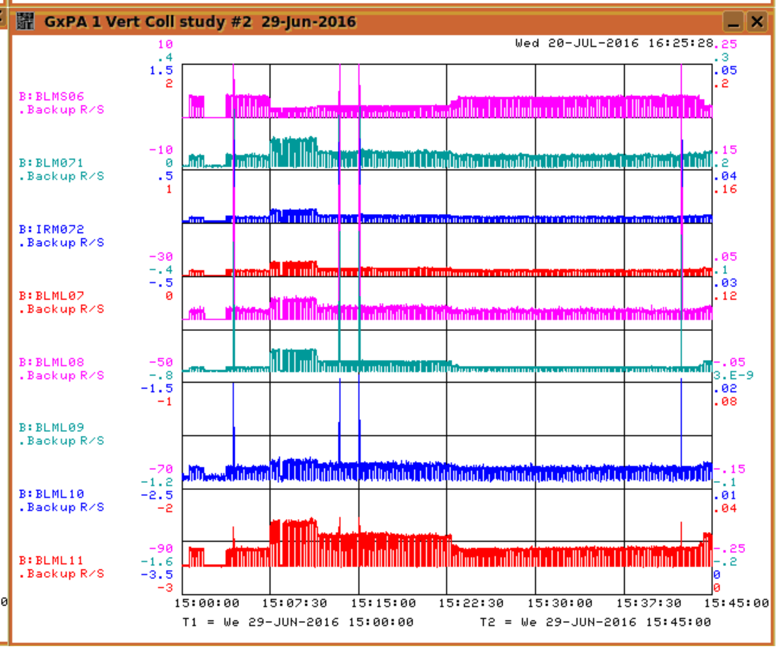

D44:

AL7AG1
AL6BG1

&
Coll.
positions

BLMs
In D43
list:
L05,
051,
S05
052,
061
062
063
L06



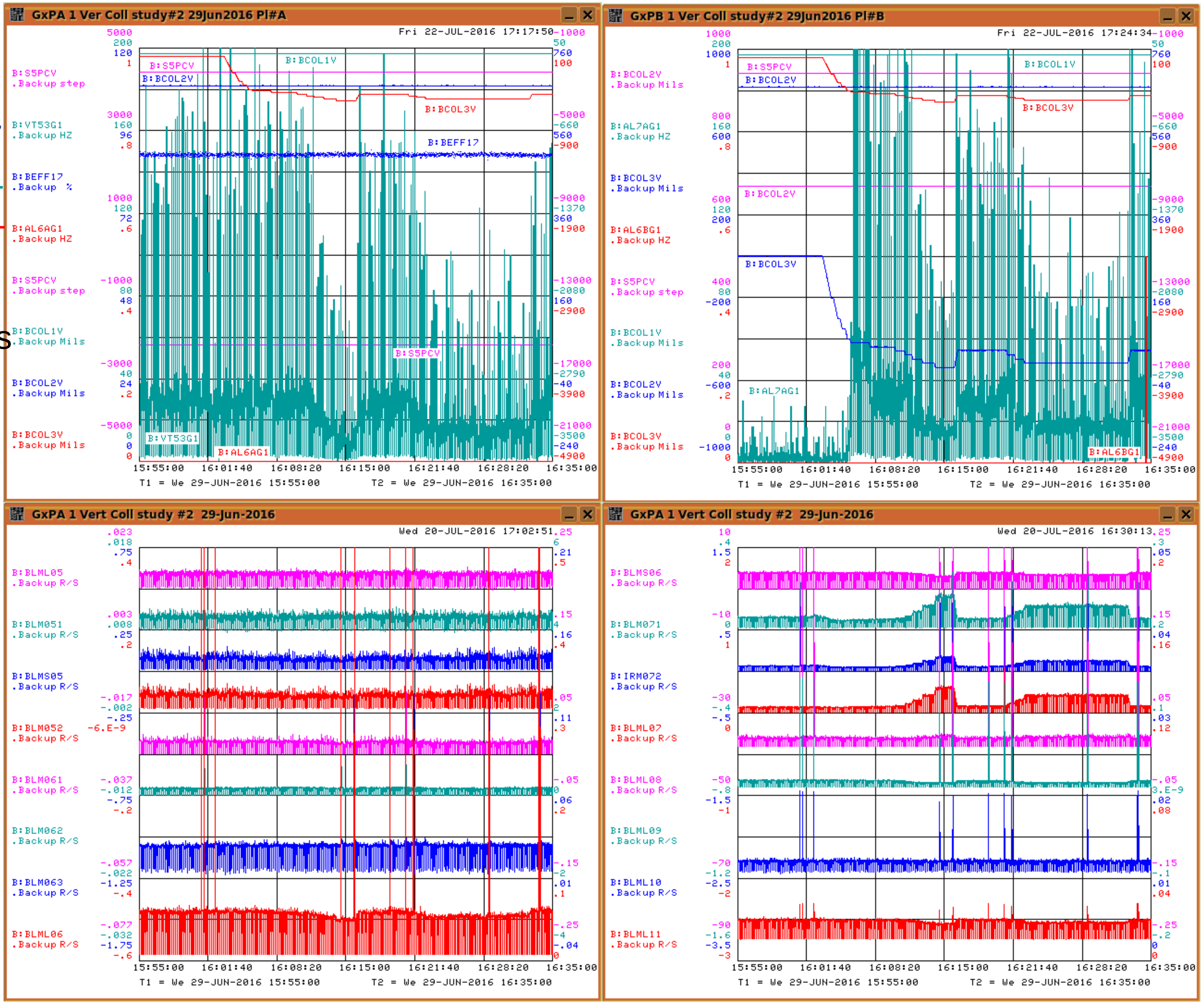




BLMs
In D43
list:
S06,
071,
072,
L07
L08
L09
L10
L11

# Tuning Col3-L7A: “g”-interval (15:55-16:35)

D44:

BEFF17
VT53G1
AL6AG1
&
Coll.
positions



D44:

AL7AG1
AL6BG1

&
Coll.
positions

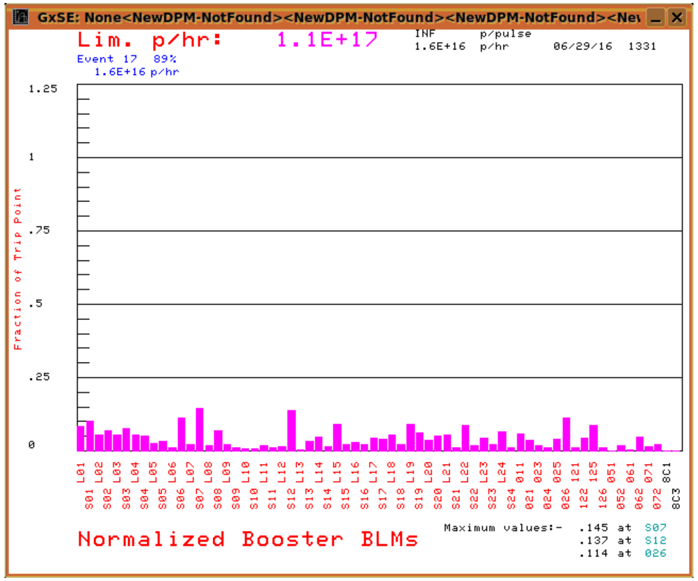
BLMs
In D43
list:
L05,
051,
S05
052,
061
062
063
L06

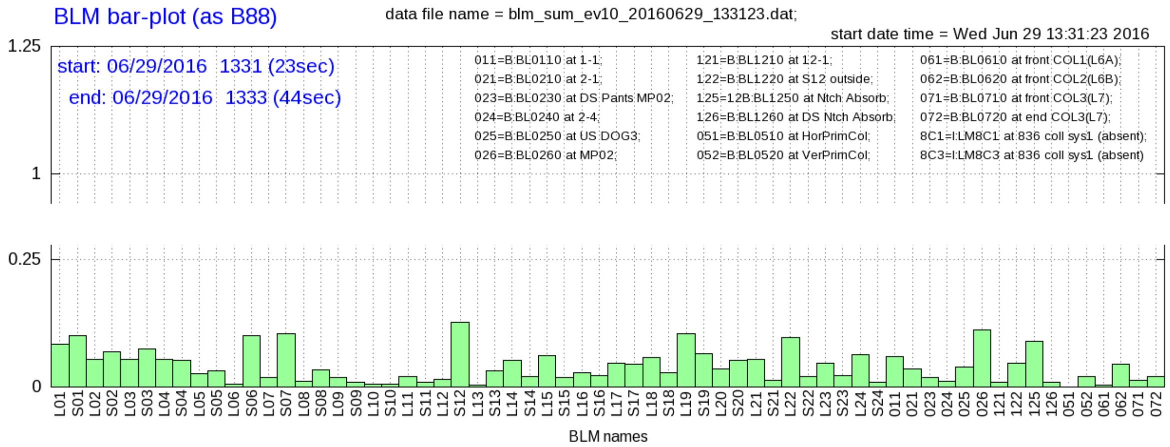
BLMs
In D43
list:
S06,
071,
072,
L07
L08
L09
L10
L11

# Plot “Frac. trip point” B88

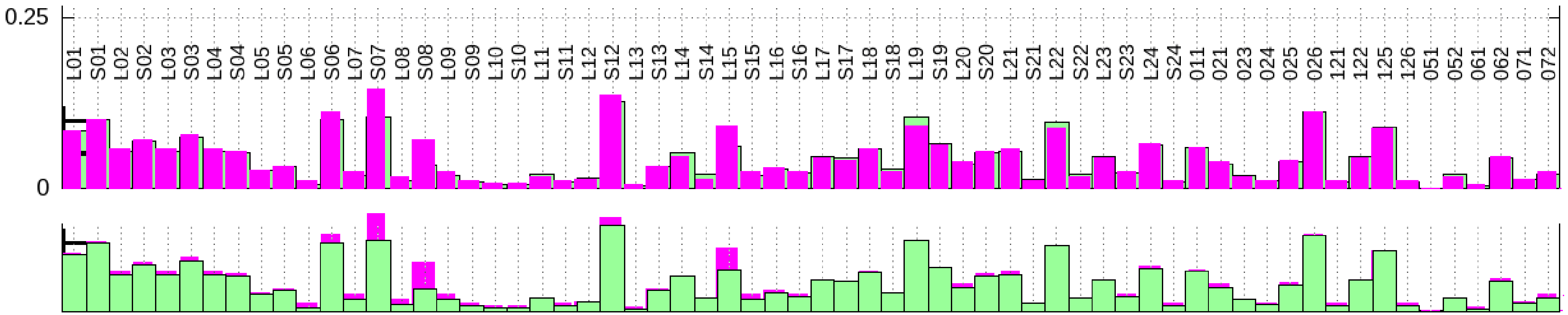
B88 Data export does not work =>
only “PrintScreen” (snapshots)
Data of B136 recommended by Kent

a’la “B88”: for **numerical comparisons** of loss-patterns I wrote code for linux. It reads BLM data to reproduce B88 plots (~1.5min)



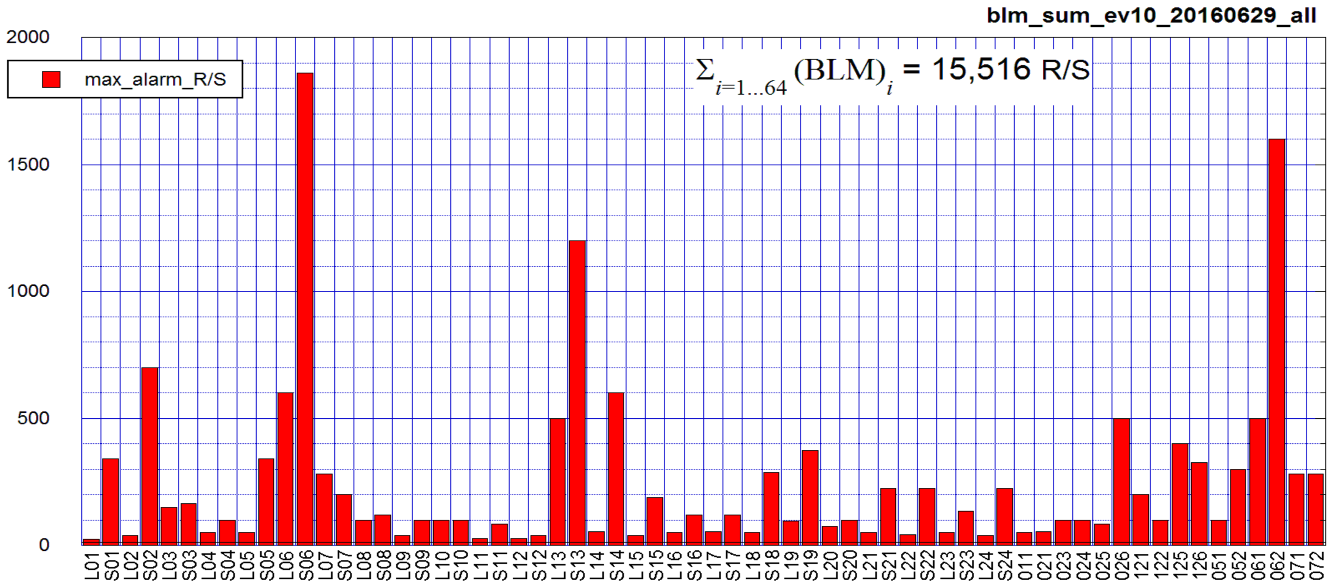




Check coincidence by overlapping:



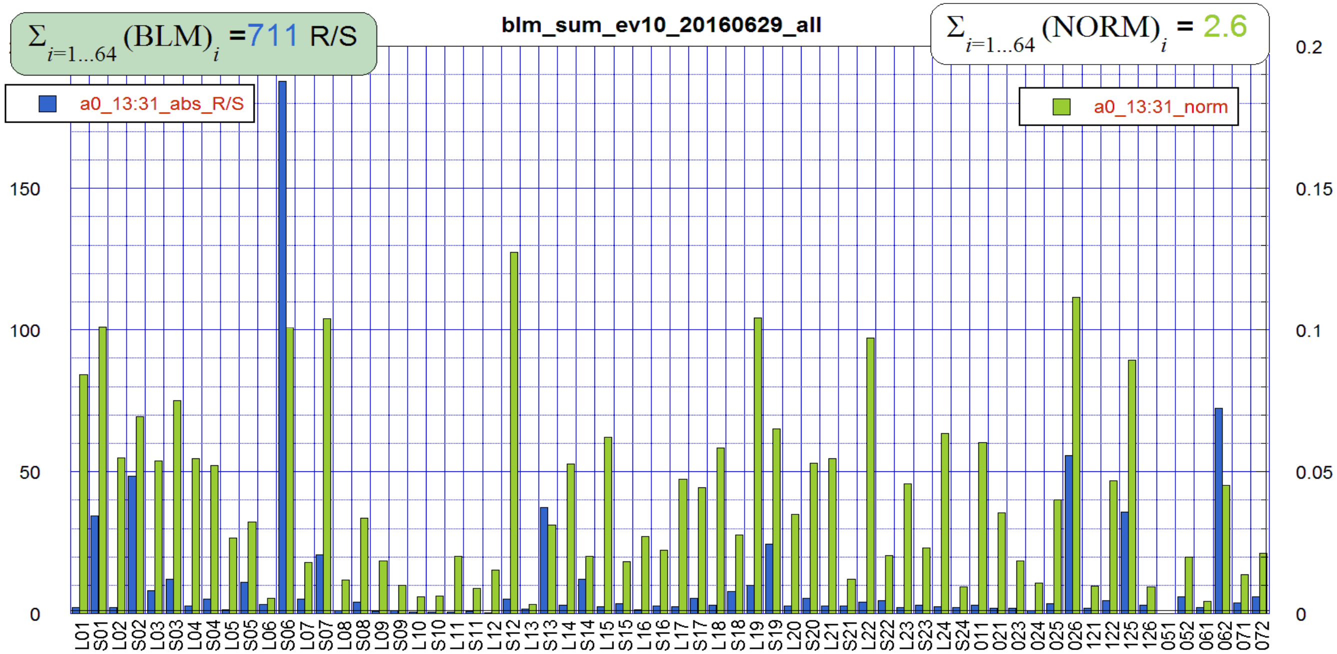
# Data used to create "a'la B88" tripping plots

Absolute Alarm (trip) values

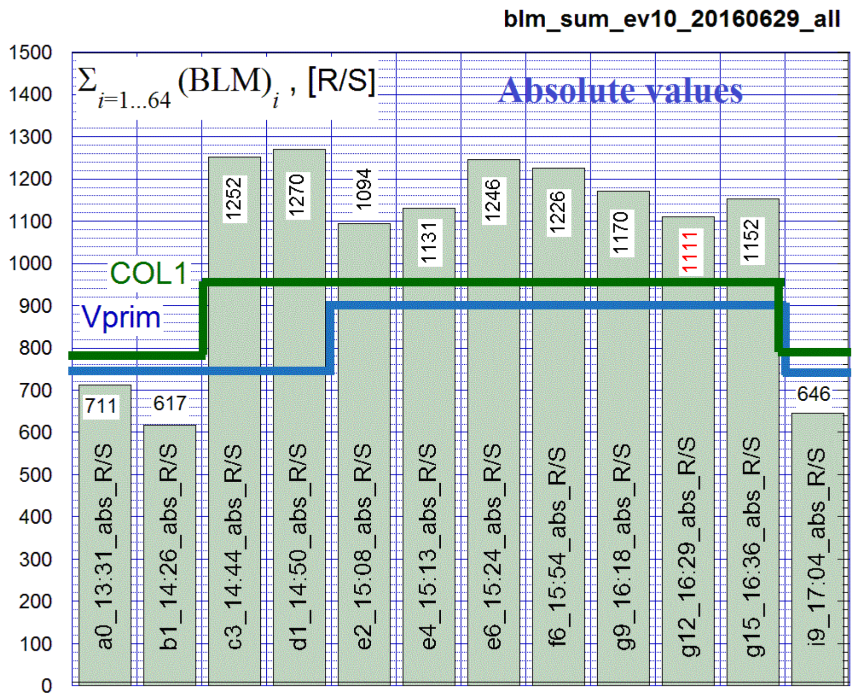


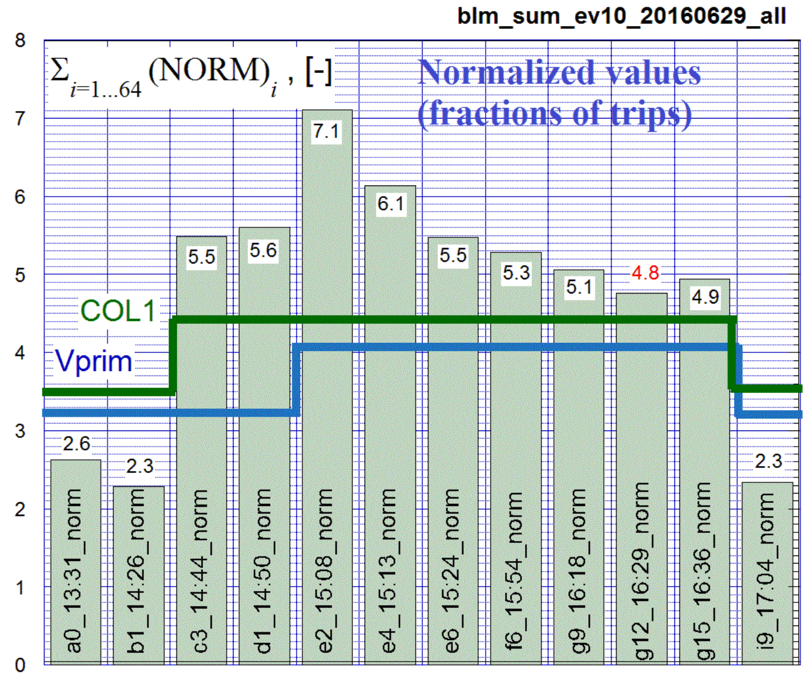

Distributions for absolute and normalized (fractions of trip) values looks very different

Sum of all (or part) Available !



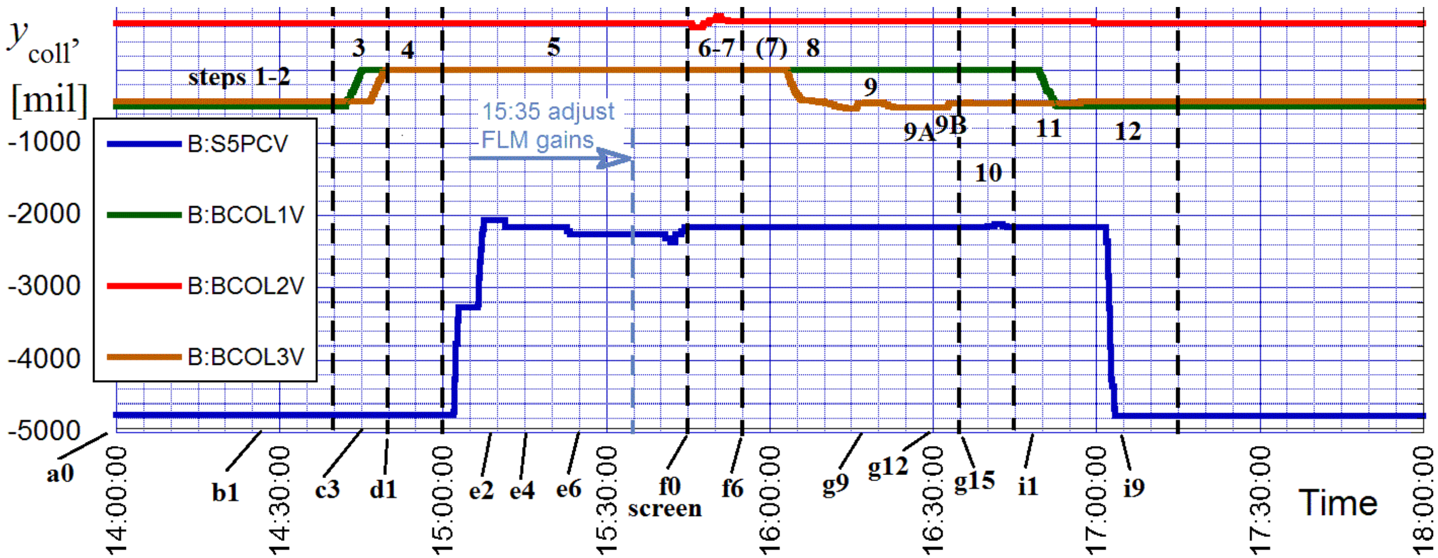
# Loss distribution comparison




G12&b1:
1111/
617
=1.8

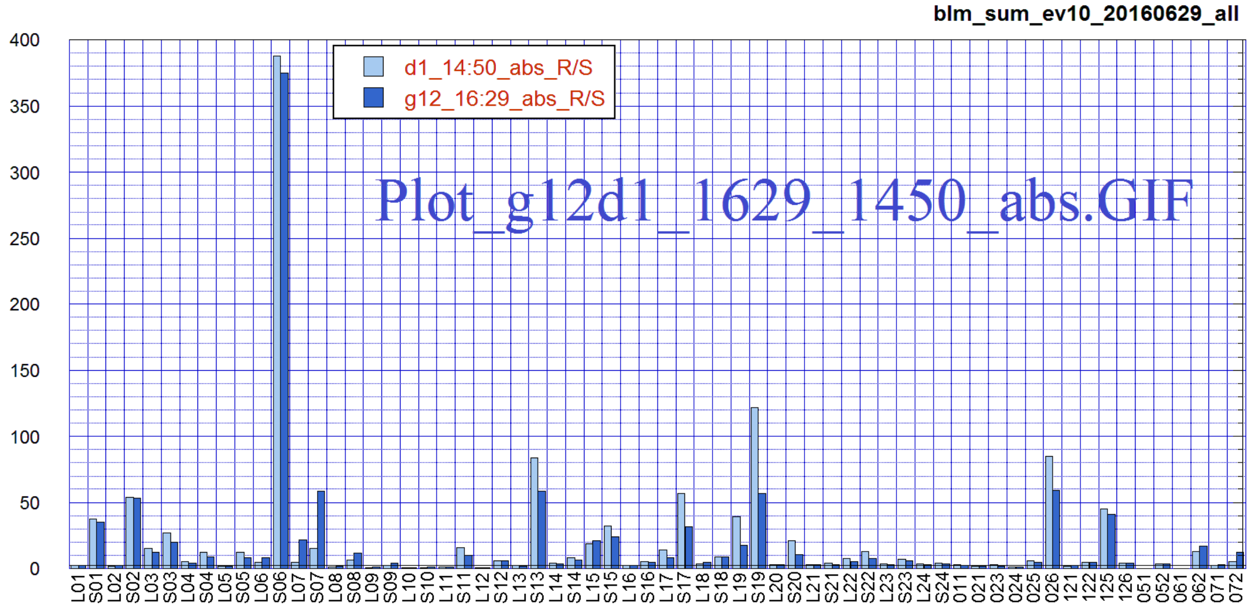
G12&d1:
1111/
1270=
0.87

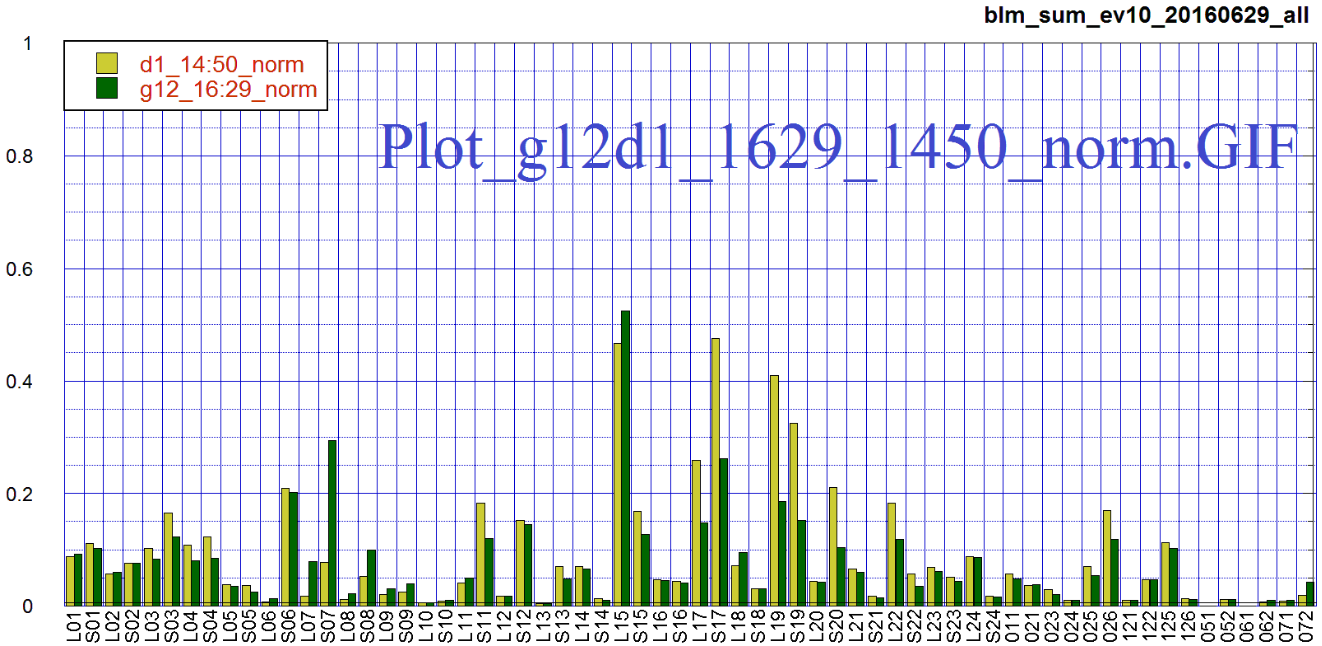



G12&b1:
4.8/2.3
=2.1

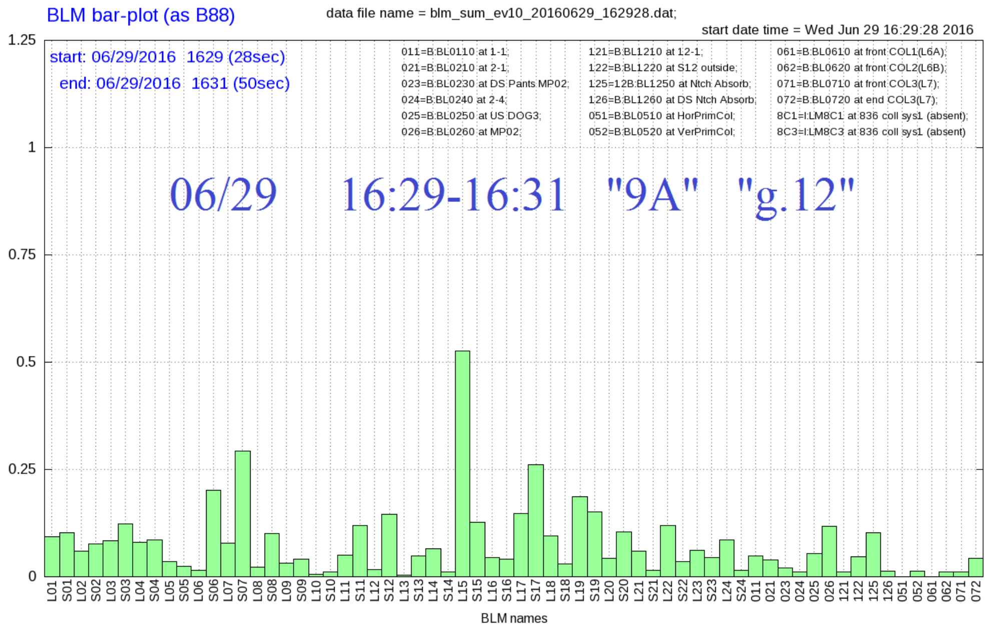
G12&d1:
4.8/5.6=
0.86

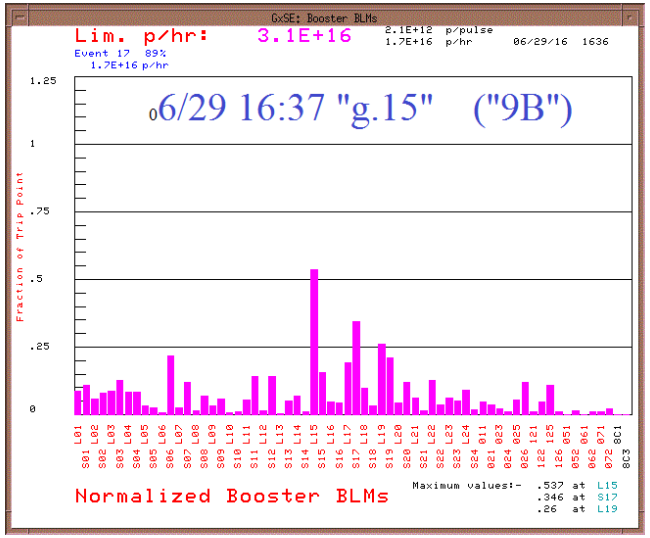
# Plots for “local” optimization “g12 vs d1”



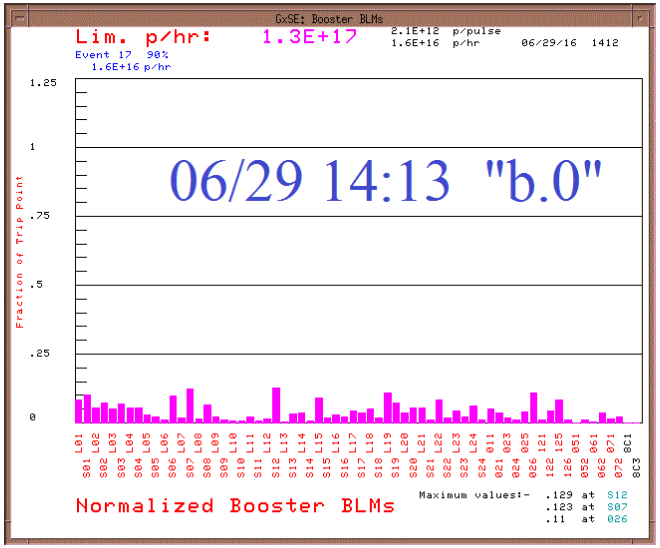



# Comparison with initial “g12 vs b1”



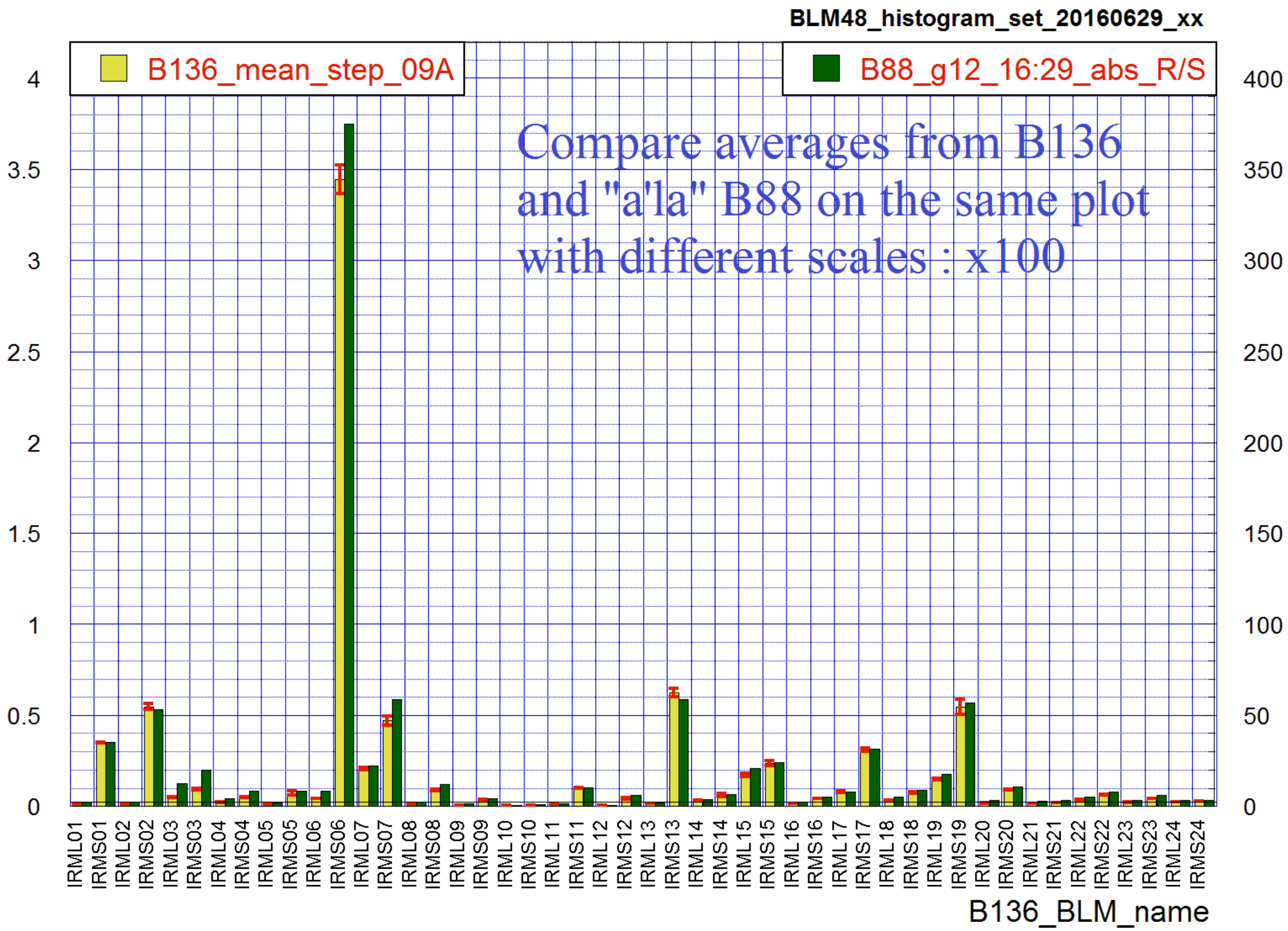



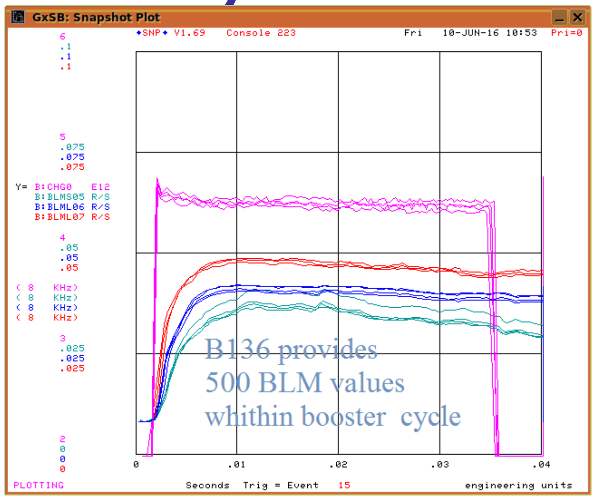




# B136 BLMs signal within Boo-cycle

Save data => postproc. Code: check bad curves (see last presentation);
averaging over cycle => compare with “B88:-plots



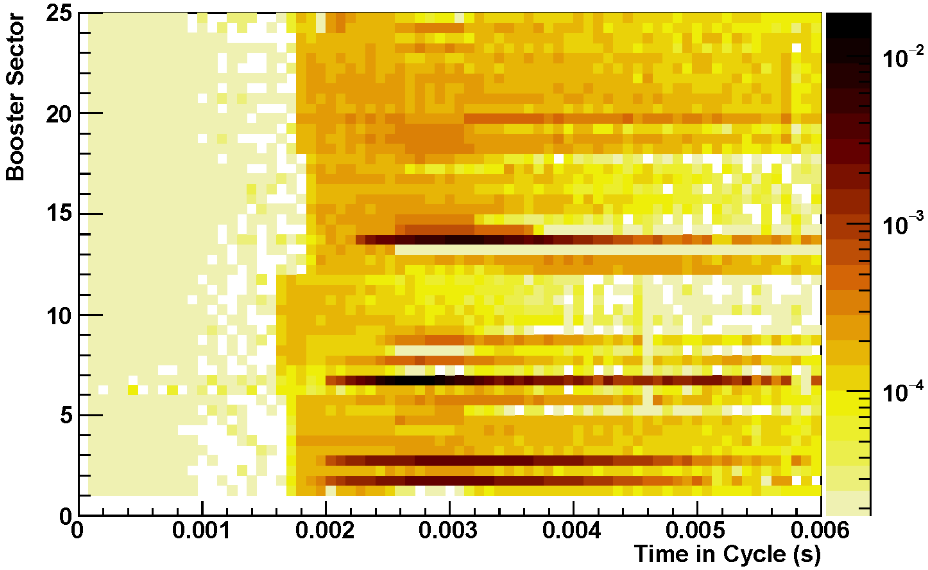

Very similar
Results
From B136
Averaging
And “B88”
plots

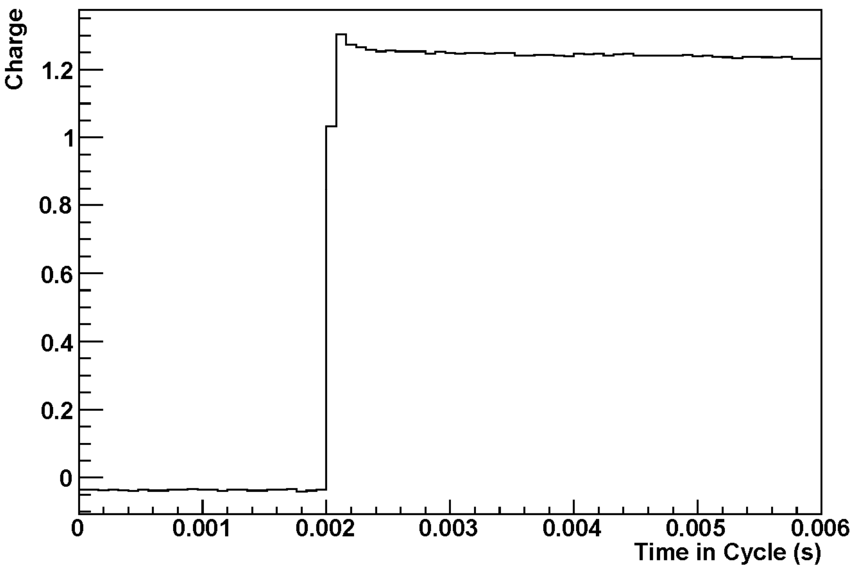
# Conclusion

- Simulations: 2SC have ~ the same efficiency (max ~60%) as 1SC at halo 10um (55%)
- 1SC may have even larger actual efficiency (if halo higher)
- Present foil is still thicker of optimal one: change to Be-foil may help reach ~60% efficiency
- Preparing for beam study: all equipment ant & pos-proc code are ready for next studies
- 29-Jun study for Vert-plane demonstrated ~twice lower efficiency for 2SC vs 1SC
- Another study for V-plane can be done if “L6A<->L6B”
- Study for Hor-plane should be also schedule
- Analytical & simulation study to understand low efficiency of existing 2SC and suggestion of new collimation are planned to start

# Additional slides

# BLM data: “initial conditions” zoomed at injection




“initial conditions” = a standard collimator settings for 1-stage.

The top plot are the instantaneous losses (diff. between consecutive readings: R(i) - R(i-1)).

The bottom plot shows the beam current.

*Some Issues:*

*1. The BLMs data are not timed relative to one another at about the 300us level (see backup slide).*

*It appears that there are two groups (sectors 1-12 and 13-24)*

*2. Loss information from specific BLMs looks strange (see top plot).*

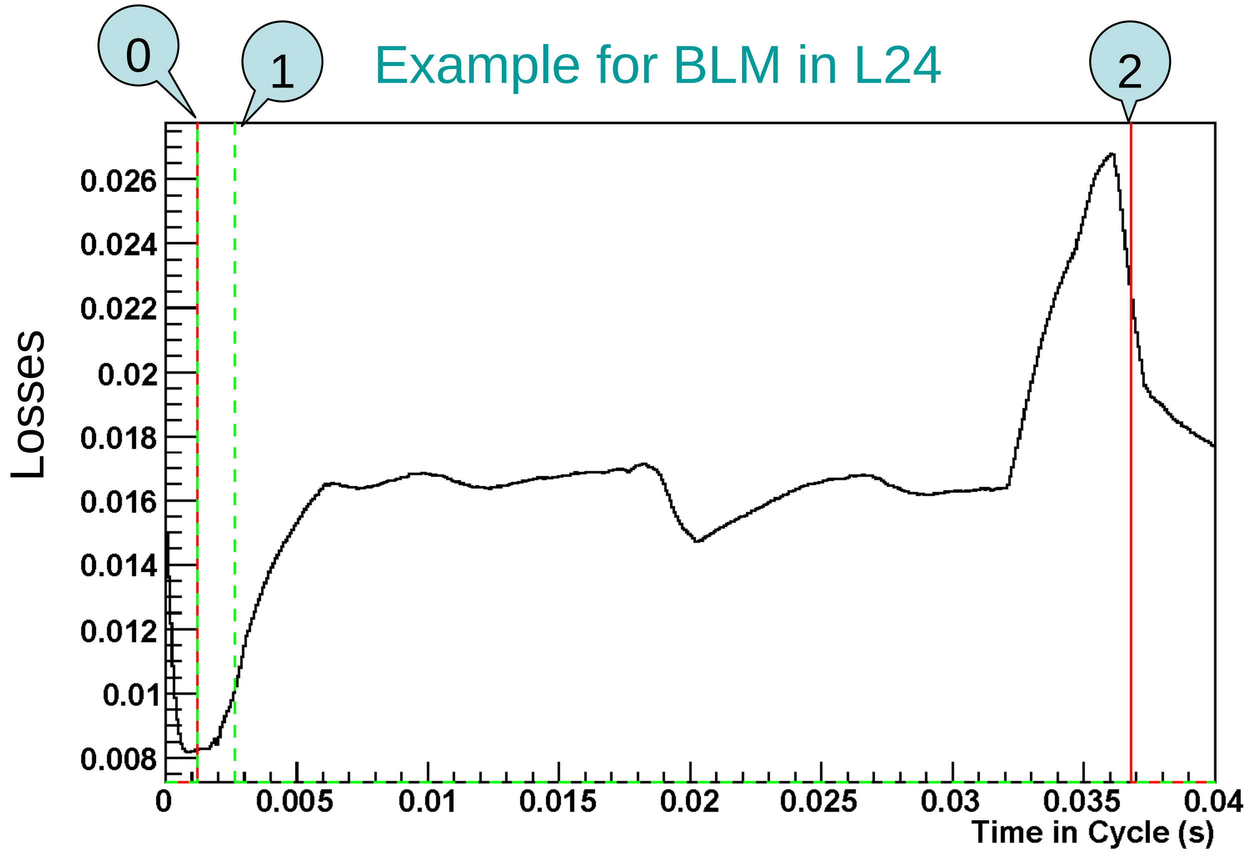
*3. The beam current has a “negative pedestal” (see bottom plot).*

# BLM post-processing: definitions

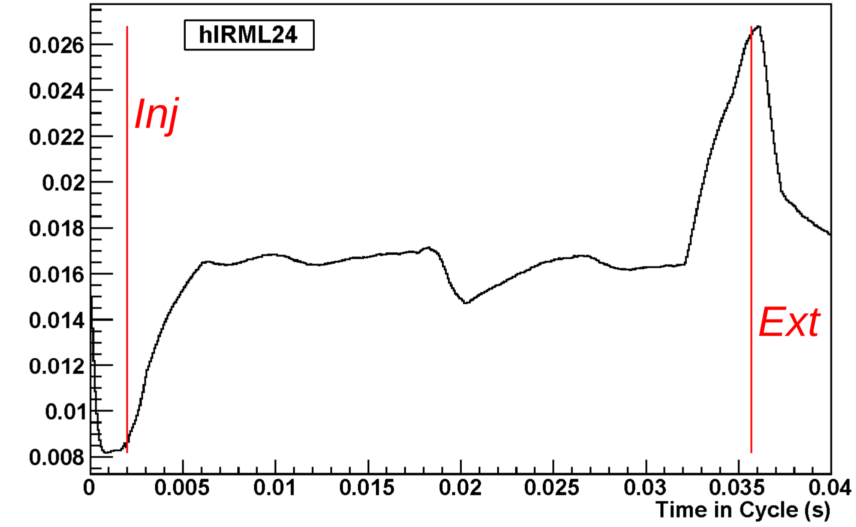
Booster Loss profiles (losses vs BLM number)

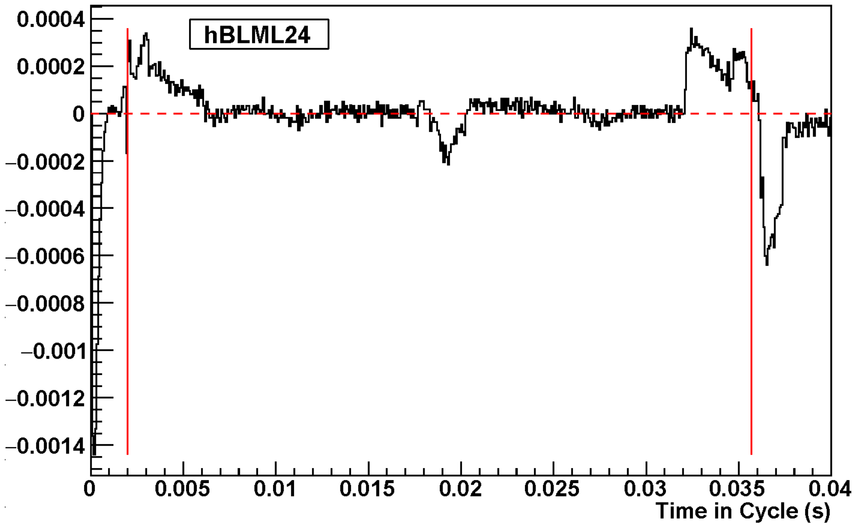
Inj. Losses = Loss(1) –Loss(0)

Tot. Losses = Loss(2) –Loss(0)



# Example: BLM in L24



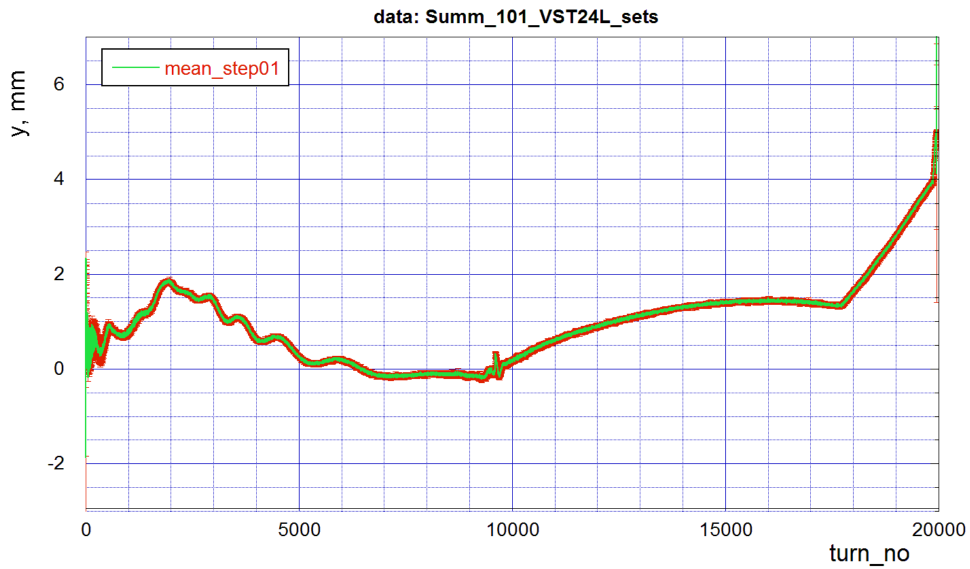




Integrated losses (top) and instantaneous losses (bottom).

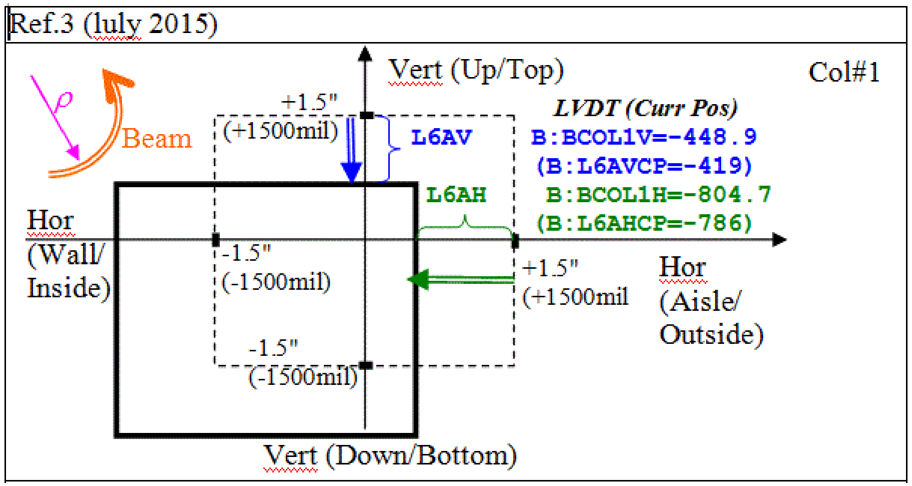
*Red lines: injection & extraction*

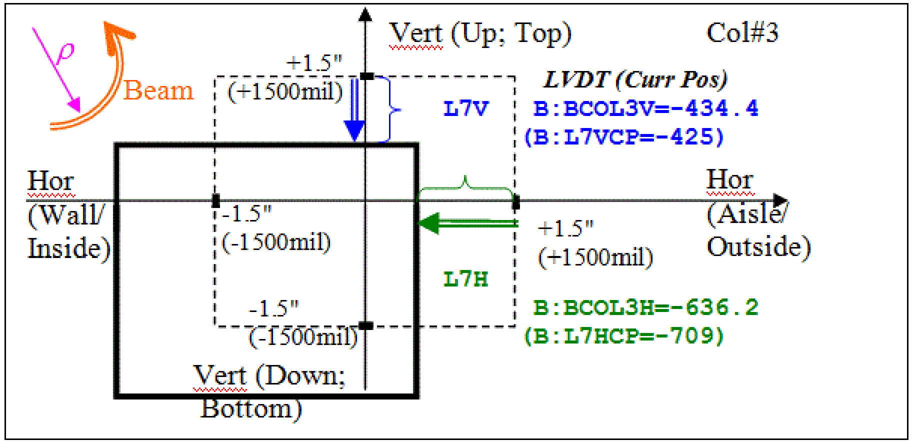
Issues:
fast drops of integrated losses
Negative values of differential (instantaneous) losses

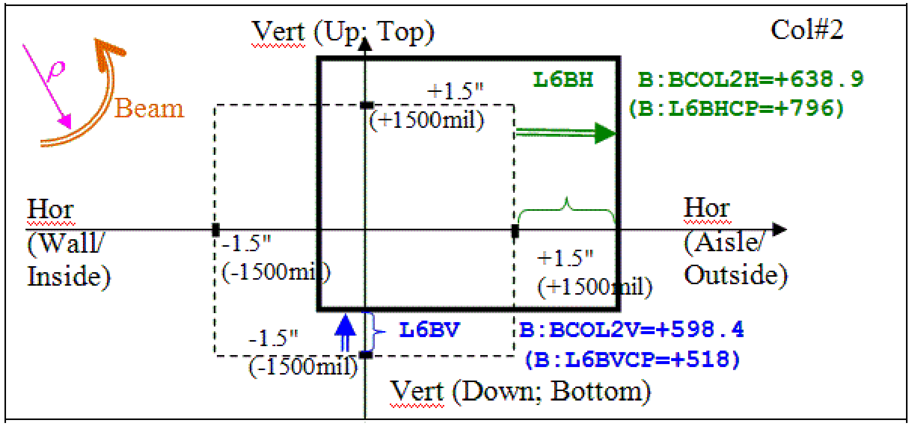
*Vert. orbit in L24*

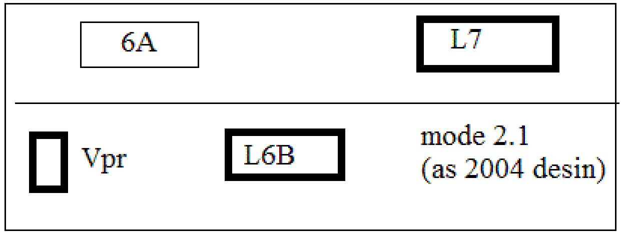


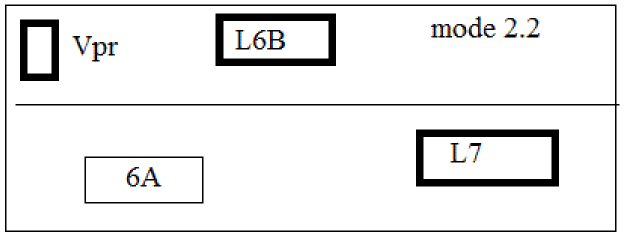
# Connection Coll LVDT & modes



# Principle scheme of 2-stage collimation system

Usual "1-stage" collimation produces uncontrolled out-scattered protons =>
"2-stage" scheme

Bryant, in CERN Acc. School (1992), p.174

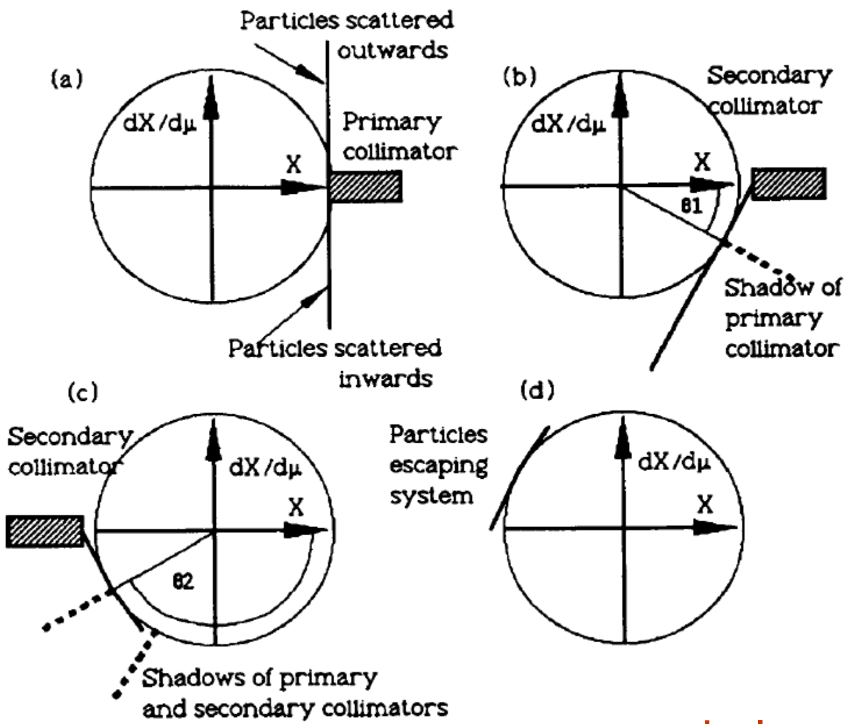



Fig. 11 Main features of a collimation system

The primary collimator is followed by two secondary collimators set at optimized phases for intercepting the scattered particles.

Simulations steps (as with STRUCT):

- ❖Generate **part. distribution** on edge of Prim-Collimator (halo-particles)
- ❖**Scattering** in material of thin P-Coll
- ❖**(Non-linear) Tracking** scattered parts
- ❖Collect **lost particles** on Sec-Colls and other magnet **apertures**

halo particles => large amplitudes =>
Correct treatment non-linear dynamics => ~MADX

# Collimator placements in booster

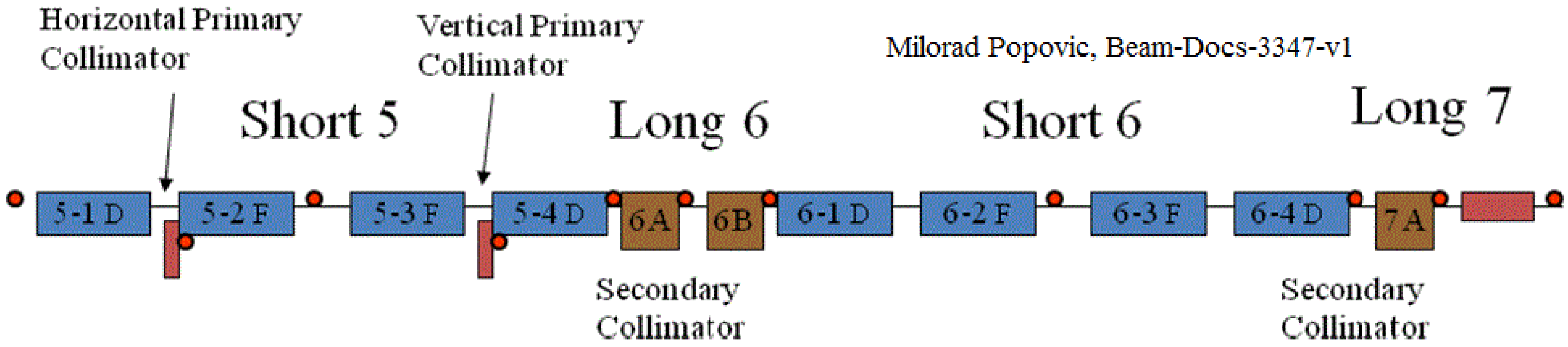
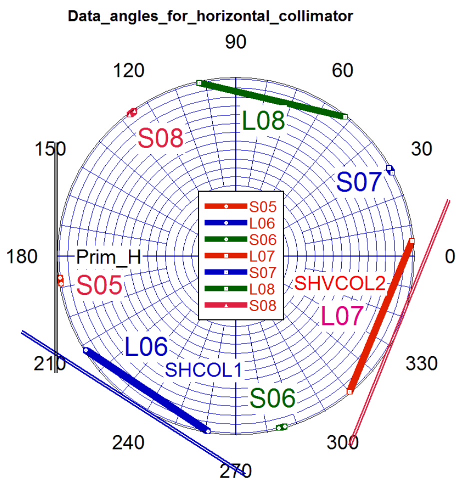
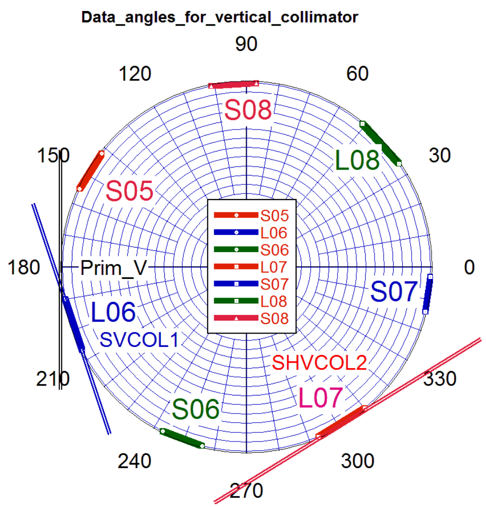



Figure 1. Blue boxes represent the main magnets; collimators are represented by brown boxes.




Restrictions for design:

Not optimal phase advances;

Small magnet apertures;

Bending magnets in coll system;

Variable beam parameters during accelerator cycle